MULTIMODAL INVESTIGATION OF MIND WANDERING AND ATTENTION LAPSES

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MULTIMODAL INVESTIGATION OF MIND WANDERING AND ATTENTION LAPSES

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SUMMARY

The neuroscience of mind wandering has advanced appreciably over the past decade. By applying convergent methods that span self-reports, behavioral indexes, and neuroimaging, researchers have been able to gain an understanding of how the brain supports ongoing mentation that is unrelated to other tasks at hand. However, despite the complex processes that attention lapses can take, research in this field has often focused on simply dichotomizing mind wandering as either on-task or off-task. Furthermore, repeated use of tasks such as the sustained attention to response task (SART) to study mind wandering has constrained research and hampered generalizability. The current work addresses these issues by presenting a novel series of thought prompts that query several attention states and dynamics as participants perform the metronome response task (Seli et al., 2013). In Study 1, simultaneous recording of behavioral performance, fMRI, and pupil diameter allowed for a multimodal investigation of the neural correlates of attention lapses. In Study 2, task difficulty was manipulated in order to test the effect of cognitive load on attention lapses and performance. Results indicated unique behavioral and neural profiles for several attention states and found subtle but consistent differences between self-reported attention state and performance variability. In addition, cognitive load modulated task performance and, to a lesser extent, the frequency of dynamic states (e.g., spontaneous versus constrained attention) in manners consistent with previous theorizing (e.g., the context regulation hypothesis). However, not all measures dissociated across attention states. The results are discussed from the perspectives of mind wandering theories and

frameworks, the function of the default mode network, and the importance of task context in the study of attention lapses.

CHAPTER 1. INTRODUCTION

The neuroscience of mind wandering has advanced appreciably over the past decade. By applying convergent methods that span self-reports, behavioral indexes, and neuroimaging (a process referred to as *triangulation*, Smallwood & Schooler, 2015), researchers have been able to gain an understanding of how the brain supports ongoing mentation that is unrelated to other tasks at hand. Whereas the default mode network (DMN) has been strongly implicated in supporting many of these processes, the role of multiple large-scale networks and their underlying dynamics has more recently been in the spotlight (Christoff, Irving, Fox, Spreng, and Andrews-Hanna, 2016). Furthermore, researchers have reliably documented the impact that failures of attention have on the task at hand. At the same time, research has emerged that suggests not all instances of mind wandering are inherently harmful (Mooneyham & Schooler, 2013).

In the current investigation, I conducted an in-depth examination of the neural mechanisms of attention lapses and tested recent theorizing regarding the dynamics of mind wandering. In addition, I examined the dichotomy of subjective attention states and behavioral performance and tested the effect of cognitive load on the prevalence and dynamics of off-task thought and other forms of distraction. This research consisted of two studies, across which I used a multimodal approach incorporating behavioral performance, functional neuroimaging, pupillometry, and self-report measures. Over the next sections, I review the literature behind mind wandering and attention lapses. I also present my methodology and analysis approach to address my research questions. To summarize the methodological approach, participants performed a continuous behavioral performance task that has been shown to index mind wandering instances reliably. Intermittently, participants were presented with thought probes and asked to self-report their current state of thought. In Study 1, pupil diameter and fMRI were collected concurrently in order to examine the pupillometric and neural correlates of attention lapses. In Study 2, cognitive load was manipulated and performance and self-reported attention states were recorded.

1.1 Current Definitions of Mind Wandering

Mind wandering research entered a new era with the rise of neuroimaging and, in particular, the discovery of the DMN. However, mind wandering has remained difficult to define scientifically. In layman's terms, mind wandering has been thought of as the undirected, daydream-like processes that people experience when they are not otherwise focused on a task at hand. In the literature, however, mind wandering has taken on different definitions depending on the researchers and the studies. As discussed in Christoff (2012), the terms "mind wandering", "spontaneous thought", and "stimulus-independent thought" have been used interchangeably yet are not equivalent. Mind wandering has often been operationally defined as "task-unrelated thought" (Mrazek, Philips, Franklin, Broadway, & Schooler, 2013; Smallwood & Schooler, 2006), but this is agnostic as to whether an instance of mind wandering is stimulus-independent or triggered by something in the environment. Similarly, stimulus-independent thought is simply that – thoughts generated by ongoing mental processes decoupled from the external environment. For example, a stimulus-independent thought can include an instance when one thinks about last summer's vacation, whereas a stimulus-dependent thought can occur when one notices the loud noises from the MRI scanner. Stimulus-independent thoughts can be undirected (arising spontaneously, such as suddenly remembering an upcoming deadline) or directed (as in planning events for the next day; Christoff, 2012).

Furthermore, one's moment-to-moment stream of consciousness is not comprised solely of either on-task thoughts or mind wandering (defined in general terms as task-unrelated thought). In the context of task performance, an individual may be completely focused on the task or may experience one of several types of lapses of attention: partaking in a mind wandering episode, thinking about topics related to the task at hand (referred to as "task-related interference", such as the thought "How much longer will this take?"), or lapsing into a drowsy, inattentive state and not thinking about anything in particular. In addition, not just the content of one's thoughts may vary on a moment-to-moment basis, but the dynamics of thoughts can fluctuate as well. A recent framework proposes that the dynamics of thoughts (i.e., how mental states change over time) need to be considered when defining and understanding mind wandering (Christoff et al., 2016; Mills, Raffaelli, Irving, Stan, & Christoff, 2017). In this framework, thoughts fall along a continuum and can range from spontaneous and freely moving (e.g., dreaming) to strongly constrained (e.g., directed problem solving). Christoff and colleagues propose that there is a low-to-medium level of constraint during periods of mind wandering. As discussed later, emphasizing the dynamics of mind wandering and other thoughts has important implications and predictions for behavior and for the neural mechanisms underlying these processes.

Unfortunately, despite the number and dynamics of different attention states that can arise, most mind wandering studies have ignored this spectrum and have only focused on a subset of these states. For example, one of the most prominent fMRI studies in the mind wandering literature, published by Christoff, Gordon, Smallwood, Smith, and Schooler (2009), only compared on-task and off-task thoughts, and whether individuals were aware of being off-task. The few studies that have examined the different types of off-task modes of attention indicate that it is still unclear how these different states may affect behavioral performance. For example, one study incorporated experience sampling with the sustained attention to response task (SART; Stawarczyk, Majerus, Maj, Van der Linden, and D'Argembeau, 2011a). The SART is a go/no-go task where participants are presented with single digit numbers and are instructed to respond quickly and accurately to each number but withhold their response to a target number (e.g., number 3). Stawarczyk and colleagues (2011a) found that reaction times (RTs) were faster for trials during on-task thoughts and task-related interference compared to external distractions and task-unrelated, stimulus-independent thoughts. However, variance in RT as well as performance accuracy did not distinguish between any type of off-task thought. Similarly, Unsworth and Robison (2016) observed faster RTs on a sustained attention task during instances of on-task reports compared to all types of off-task reports. In terms of brain activity, Vanhaudenhuyse and colleagues (2011) reported increased fMRI activation in precuneus and posterior cingulate (DMN regions) when participants reported awareness of internal thoughts and feelings, whereas increased fMRI activation was observed in frontoparietal regions when participants reported awareness of external stimuli.

To examine the neural correlates of attention lapses thoroughly and to test the effect that attention states have on performance, in the current research I approached the topics of mind wandering and other forms of distraction from a global perspective that encompasses both a range of attention states as well as their dynamics. The thought probes used in the current research provided participants with options to classify their thoughts as either on-task (i.e., focused on the task assigned by the researcher), off-task (i.e., focused on thoughts unrelated to the assigned task), as task-related interference, or indicate whether they were in a state of lack of attention or drowsiness. Participants were further able to classify their off-task thoughts as 1) either related to something in their current environment (e.g., sights and sounds) or something internal in their mind (e.g., memories or plans) and 2) as either constrained/directed or arising spontaneously. Including this range of attention states in the thought prompts provided the ability to more accurately investigate the neural correlates of attention lapses and understand how mind wandering and other attention fluctuations affect behavioral performance. In addition, this approach confers with the recent argument that mind wandering should be considered from a "family resemblances" perspective, where it is treated as a graded, heterogenous construct (Seli et al., 2018a). When referring to the current work, I use the terms *on-task, task-related interference (TRI), off-task,* and *inattention* to distinguish between these different attention states. For the characteristics of the off-task state, I use the terms *external, internal, spontaneous, and constrained.* However, in the review of the literature that follows, I use the terms "mind wandering", "off-task", and "attention lapses" interchangeably and in a more general manner, congruent with the articles referenced.

1.2 Measuring Mind Wandering with Continuous Performance Tasks

A common way to measure how much an individual mind wanders or experiences task-unrelated thoughts is through probe-caught experience sampling: The researcher presents occasional thought probes during the course of the experiment, and the participant responds to the thought probes by indicating whether their attention was on-task or off-task

(Gruberger, Ben-Simon, Levkovitz, Zangen, & Hendler, 2011; Smallwood & Schooler, 2015). Researchers then examine behavioral performance and the neural correlates during the moments preceding the off-task thought probes in comparison to on-task thought probes. As mentioned above, the SART has been a popular task choice among researchers. By combining the SART with experience sampling, researchers have documented negative correlations between SART accuracy and off-task thought (McVay & Kane, 2009; Stawarczyk et al., 2011a).

More recently, researchers have explored the extent to which behavioral tasks can capture fluctuations in attention and performance in an online manner as it happens. Being able to detect mind wandering as it happens has both theoretical and practical purposes, in that it may provide a means of detecting and then intervening as it occurs (Seli et al., 2013). Online detection of mind wandering could also enable improved understanding of the dynamics of mind wandering, as well as provide a means in which researchers can study mind wandering without relying on self-reports. In particular, researchers have examined how variability across continuous performance can be used as an indicator of mind wandering (Cheyne, Solman, Carriere, & Smilek, 2009; McVay & Kane, 2009; Seli et al., 2013). For example, the SART can be analyzed with respect to RT variability. Henriquez, Chica, Billeke, and Bartolomeo (2016) observed abrupt increases in RT variability on go-trials preceding mind wandering reports. Bastian and Sackur (2013) also administered the SART and calculated the coefficient of variability on the eight go-trials preceding each thought probe. They observed that increased RT variability preceded mind wandering reports, regardless of whether the particular mind wandering instance was self-caught or queried with a thought probe.

Seli and colleagues (2013) extended this line of research. They developed the metronome response task (MRT) where participants tapped along to the sound of a metronome. Participants were also intermittently queried as to whether they were on-task or were mind wandering. To examine continuous performance variance, Seli and colleagues calculated for each tap the difference between each metronome onset time and its corresponding button press (referred to as rhythmic response time; RRT). They then calculated the RRT variance of the five taps preceding each thought probe. They observed increased RRT variability preceding instances when participants reported mind wandering.

The work of Seli and colleagues (2013) and others (e.g., Bastian & Sackur, 2013) demonstrate that mind wandering can be indexed with continuous performance variability. Furthermore, the MRT developed by Seli and colleagues overcomes a number of limitations present in tasks that are commonly used to study mind wandering, such as the SART. The SART requires both response selection and response inhibition, and the rare critical trials may influence mind wandering processes (Cheyne et al., 2009). In addition, performance on the SART requires a speed-accuracy tradeoff, which may confound continuous patterns of performance indicative of mind wandering (Seli et al., 2013). In general, the MRT is a simple yet effective task that can index mind wandering processes and provide a method for investigating the effect of attention fluctuations on behavioral performance in an online manner. For the present work, I incorporated the MRT with the extended set of self-report attention categories described above. This combination allowed me to expand upon the results of Seli and colleagues (2013) by examining a broader range and dynamics of attention lapses. Furthermore, the MRT is amendable to cognitive load manipulations. In Study 2, I included both an easy and difficult version of the MRT to examine the effect of task difficulty on performance and attention states.

1.3 Behavioral Characteristics of Mind Wandering and Attention Lapses

A large amount of early research investigated behavioral and personality characteristics associated with mind wandering and related attention processes (e.g., daydreaming). Influenced by signal detection and vigilance research[1], Antrobus, Coleman, and Singer (1967) recruited participants with high and low tendencies to daydream and administered a vigilance task where participants responded to one of two auditory tones. Participants were also presented with thought probes and indicated whether they experienced any task-irrelevant thoughts. Antrobus and colleagues observed that high daydreamers reported more off-task thoughts and low daydreamers reported fewer off-task thoughts. The researchers also observed a significant difference in performance at the end of the task between the two groups, in that high daydreamers performed significantly worse at the end of the task compared to low daydreamers.

Singer and Schonbar (1961) found that daydream frequency positively correlated with several characteristics, including night dream recall frequency, thematic creativity, achievement need, and anxiety. Singer and McCraven (1961) surveyed university students and found that the predominant content of daydreams consisted largely of practical concerns, and often were composed of visual imagery and oriented to the future. Klinger

[1]Note that along with mind wandering research, there is a large literature on vigilance, where performance decrement might reflect mind wandering as well. However, the literature reviewed in this manuscript is constrained to research on mind wandering and attention lapses studied with self-report.

and Cox (1987) used experience sampling to study characteristics of thought in daily life. Similar to Singer and McCraven, Klinger and Cox found that thoughts were predominantly visual. The researchers observed that thoughts also often consisted of an inner monologue. In addition, thoughts were reported as either directed or undirected and either stimulus-independent or dependent.

More recent research further builds on the behavioral characteristics associated with mind wandering. Typically, mind wandering is a negative consequence of failing to maintain attention to the task at hand. Mind wandering has been negatively correlated with poorer performance on a variety of tasks measured in the laboratory (e.g., working memory tasks and RT variability on continuous tapping tasks; McVay & Kane, 2009; Seli, Cheyne, & Smilek, 2013) as well as with performance on tasks that can occur outside the laboratory (e.g., SAT scores and reading comprehension; McVay & Kane, 2012; Mrazek et al., 2012). For example, Mrazek and colleagues (2012) found that mind wandering frequency measured during the administration of working memory and fluid intelligence tasks was negatively correlated with performance on the SAT taken one to three years earlier. Within the laboratory, Kucyi, Esterman, Riley, and Valera (2016a) observed increased RT variability in association with mind wandering. In this study, participants performed the gradual continuous performance task (gradCPT) in which they viewed gradually changing images of scenes. Participants were instructed to press a button for each city scene and withhold the button press for each mountain scene. Kucyi and colleagues observed positive correlations between increased off-task ratings at the end of each task block and both RT variability and commission errors. Similarly, in a SART experiment, Bastian and Sackur (2013) observed increased RT variability during the eight trials preceding mind wandering reports compared to on-task reports. Seli and colleagues (2013) observed increased performance variability during probe-caught mind wandering states compared to task-focused states during performance of the MRT. In general, a close correspondence has been documented between diminished behavioral performance and mind wandering.

However, mind wandering is not always associated with negative performance, and negative performance does not always indicate mind wandering. For example, Henriquez et al. (2016) observed increased RTs during instances of mind wandering in a sustained attention task. However, they also reported that 23% of slow RTs occurred during reported on-task instances. In addition, in the continuous performance task described above, Kucyi and colleagues (2016a) observed periods of mind wandering that corresponded with low performance variability. Furthermore, and as discussed in the next section in more detail, the effect of mind wandering on performance has been shown to interact with the cognitive load of the task at hand (Seli, Konishi, Risko, & Smilek, 2018b). In general, mind wandering and other attention lapses fluctuate throughout a task. Although mind wandering is strongly coupled with drops in performance, there does not always need to be a one-to-one correspondence between attention lapses and performance. Rather, individual differences (e.g., working memory capacity, Levinson et al., 2012) and, as discussed in the next section, various task characteristics such as the level of task demand (Seli et al., 2018b) play an important role (Godwin et al., 2017).

1.4 Cognitive Load, Performance, and Mind Wandering

The frequency of mind wandering, and the extent to which mind wandering can adversely affect performance, can be modulated by various characteristics of the task at hand. A consistent finding in research is that individuals tend to mind wander while engaged in easy tasks compared to difficult tasks. Early research by Antrobus (1968) demonstrated that the frequency of stimulus-independent thoughts decreased as a tone detection task increased in difficulty (i.e., as the number of tones and the presentation rate of each tone increased). Teasdale, Proctor, Lloyd, and Baddeley (1993) found that increases in memory load and presentation rate attenuated the frequency of stimulus-independent thought.

More recently, an experiment by Forster and Lavie (2009) was conducted with an emphasis on perceptual load and mind wandering. In this task, participants performed a visual search task under low and high perceptual load and reported whether their thoughts were on-task or off-task. Forster and Lavie observed a decrease in the number of task-unrelated thoughts for the high perceptual load condition. Using a similar procedure, Levison, Smallwood, and Davidson (2012) examined individual differences and mind wandering under low and high perceptual load. Levison et al. observed that individuals with greater working memory capacity reported increased task-unrelated thoughts under low perceptual load, suggesting that when a task is relatively easy for an individual, and when that individual has high working memory capacity, he or she can lapse into a state of mind wandering while still maintaining performance on the task at hand.

Other research has also examined the effect of task demand on mind wandering. In Smallwood et al. (2009), participants reported more task-unrelated thoughts when performing an undemanding choice response task than when performing a working memory task. Despite the increase in off-task thoughts in the choice response task, performance was higher in this condition as well. Similar patterns of task-unrelated thoughts were observed across tasks in a related study (Smallwood et al., 2011). To take a closer look at the effect of cognitive load on mind wandering, Seli, Risko, and Smilek (2016) manipulated the difficulty of the SART by making the presentation of the digits either random or predictable. Throughout the task, participants were presented with thought probes asking about their attention focus, including whether their off-task thoughts were intentional or unintentional. Seli and colleagues observed an increase of intentional off-task thoughts during the easy condition and an increase of unintentional off-task thoughts during the difficult condition.

The relationship between cognitive demand and mind wandering has been important for theory-driven research in mind wandering. In regard to mind wandering theories, a handful of prominent theoretical models have been developed to explain the cognitive processes of mind wandering and the role of executive control. Smallwood and Schooler (2006) proposed the Attentional Resources account and argued that mind wandering consumes executive resources. More specifically, in this account, executive control does not initiate mind wandering episodes, but rather can be recruited to sustain thought that is decoupled from the primary task but which may be related to other goals of the individual (Smallwood & Schooler, 2006). In this sense, mind wandering would be more frequently observed in easy tasks, where there would be sufficient remaining executive resources to guide off-task thought with little or no detriment to performance. In contrast, McVay and Kane (2010) argued in their Executive Control Failures x Concerns account that mind wandering represents a failure of executive control to combat interfering thoughts. In this sense, mind wandering decreases during challenging tasks because of the increase of executive control mechanisms that guide task processing and defend against interfering off-task thoughts (McVay & Kane, 2010). A more recent perspective on mind wandering has attempted to reconcile the different implications of the models described above. Smallwood (2013) suggested that it is important to distinguish *how* mind wandering occurs and *why* it occurs. Mind wandering may often occur because of failures of executive control to inhibit distracting thoughts, as argued by McVay and Kane (2010). However, once initiated, mind wandering may continue due to decoupling from the external environment and due to control processes directing off-task thought towards other goals and concerns of the individual (Seli et al., 2018b; Smallwood, 2013).

To further address the role of executive function in mind wandering, Smallwood and Andrews-Hanna (2013) recently proposed the context regulation hypothesis: When cognitive demand is high, executive function is employed to suppress mind wandering; when cognitive demand is low, executive function mechanisms can be allocated to guide task-unrelated thoughts without necessarily a detriment to task performance. In this sense, the context regulation hypothesis can also predict the types of off-task thoughts one may experience during a particular task. For example, this hypothesis predicts that future-oriented thought, which often includes executive function processes such as autobiographical planning (Smallwood & Schooler, 2015), occurs less frequently when a task places high demand on executive function. Indeed, this effect was observed by Smallwood et al. (2009): Participants reported fewer future-oriented thoughts during a working memory task compared to passive viewing and choice RT tasks. Predictions generated from the context regulation hypothesis can also be extended to the dynamics of thought. As discussed below, spontaneously-driven thoughts are likely generated by hippocampal and medial temporal lobe mechanisms and occur with little control or effort

(Ellamil et al., 2016). Conversely, the processes supporting constrained, or directed, thoughts likely involve executive control processes to drive this dynamic of thought content in a directed, top-down manner (Christoff et al., 2016). Therefore, one prediction is that constrained thoughts are more likely, and less deleterious to performance, under low cognitive demand than high cognitive demand.

1.5 Neural Mechanisms of Mind Wandering and Attention Lapses

The DMN is the most commonly implicated brain network in mind wandering. The DMN is a set of functionally connected brain regions including the medial prefrontal cortex, medial temporal lobes, and posterior cingulate and precuneus. The DMN was first documented as a brain network that decreases its activity during externally-directed, attention demanding tasks when compared to periods of awake rest (Gusnard & Raichle, 2001; Raichle, 2001; Raichle, 2015). Following its discovery, the DMN has been frequently associated with instances of mind wandering and related spontaneous thought processes (Andrews-Hanna, Smallwood, & Spreng, 2014; Andrews-Hanna, Reidler, Sepulcre, Poulin, & Buckner, 2010; Christoff et al., 2009; Mason et al., 2007; Stawarczyk, Majerus, Maquet, & D'Argembeau, 2011b). For example, Mason and colleagues (2007) observed a greater number of reported mind wandering instances during a practiced task compared to a novel version of the same task. When participants completed the practiced and novel task versions during fMRI acquisition, the researchers reported greater DMN recruitment during the practiced tasks, suggesting that the DMN is associated with mind wandering processes (Mason et al., 2007). To more directly assess the relationship between mind wandering and the DMN, Christoff and colleagues (2009) incorporated experience sampling with the SART while collecting fMRI data and observed increased DMN recruitment during off-task thoughts. Additional research has used retrospective questionnaires after the completion of a scan to assess mind wandering and its relationship with the DMN (e.g., Andrews-Hanna, Reidler, Huang, & Buckner, 2010). Although the DMN has been strongly implicated in mind wandering processes, more recently it has been posited to support a broad range of internally-directed cognitive processes and self-generated content (Spreng, 2012; Zabelina & Andrews-Hanna, 2016), including problem solving (Gerlach, Spreng, Gilmore, & Schacter, 2011), planning (Spreng, Stevens, Chamberlain, Gilmore, & Schacter, 2010), and creative idea generation (Ellamil, Dobson, Beeman, & Christoff, 2012).

However, the DMN is not the only network likely involved in mind wandering. Activation in the frontoparietal control network (FPCN), which consists of executive control regions such as the dlPFC and anterior inferior parietal lobule, has been reported along with DMN activity during instances of mind wandering (Christoff et al., 2009). Although the FPCN has traditionally been associated in opposition to the DMN and off-task thought (Fox et al., 2005), a growing consensus suggests that the FPCN can couple with the DMN to guide periods of mind wandering that involve goal-directed cognition (Christoff et al., 2016; Fox, Spreng, Ellamil, Andrews-Hanna, & Christoff, 2015; Zabelina & Andrews-Hanna, 2016). In a recent meta-analysis of fMRI studies investigating mind wandering, Fox and colleagues concluded that along with the DMN, mind wandering is likely further supported by mechanisms involving the FPCN, the secondary somatosensory cortex, insula, and lingual gyrus (Fox et al., 2015). Christoff and colleagues (2016) extend this further. As discussed earlier, mind wandering can be characterized by the dynamics of thought, such as whether thoughts are driven spontaneously or are constrained by top-down processes (Christoff et al., 2016). In their recent framework, Christoff and colleagues (2016) propose a set of relationships between thought dynamics and large-scale brain networks. Specifically, spontaneous, internally-oriented thoughts are driven by the medial temporal lobe regions of the DMN which strongly influence other DMN regions along with the salience network. However, there is little influence from top-down control regions such as the FPCN. Conversely, during deliberate, constrained thoughts, the FPCN exerts strong influence on the DMN and salience network. This then minimizes the influence of the medial temporal lobes on the variability and spontaneity of thought. Despite this framework, to date no empirical research has investigated the neural correlates of constrained and spontaneous thought (Andrews-Hanna et al., 2017). Another goal of the current study is to test this set of relationships outlined in the framework of Christoff et al. (2016).

Regarding attention states more generally, researchers have also documented sets of brain regions associated with internal and external awareness. As described above, Vanhaudenhuyse and colleagues (2011) reported increased fMRI activation in precuneus and posterior cingulate (DMN regions) when participants reported awareness of internal thoughts and feelings, whereas increased fMRI activation was observed in FPCN regions when participants reported awareness of external stimuli. Dixon, Fox, and Christoff (2014) further summarized the distinction between internally and externally directed cognition and associated a set of brain regions with each process. Internally directed cognition involves the regions of the DMN along with the MTL. These regions support many different internally-directed processes including self-referential thought, memory retrieval, and simulating future events. Externally directed cognition involves primary and associative visual and auditory cortices for processing incoming sensory information, and primary motor and premotor regions for action associated with external stimuli. In addition, attention regions including the FEF and IPS are important for externally directed cognition due to their roles in enhancing processing of spatial locations and stimuli (Dixon et al., 2014). Dixon et al. also highlight the role of the lateral PFC, which supports both internally and externally directed cognition. In particular, this region is typically recruited during instances of intentional, top-down cognitive processes and guides internally and externally directed cognition based on the current goals of the individual.

Finally, research has begun to examine how brain networks support fluctuations in attention toward and away from particular tasks. Hasenkamp, Wilson-Mendelhall, Duncan, and Barsalou (2012) employed a meditation task and observed that certain brain networks correspond to different stages of attention fluctuations. Specifically, the researchers investigated four stages: mind wandering, awareness of mind wandering, shifting of attention, and sustained attention. Similar to previous research, activation in the DMN was observed during mind wandering, and activation in regions of the FPCN was observed when participants focused on the task. In addition, activation in right dorsolateral PFC and lateral inferior parietal regions was observed when participants shifted their attention back to the task, suggesting that regions of the FPCN may be recruited to transition from an off-task attention state back to a task-focused state.

Christoff and colleagues (Christoff et al., 2016; Ellamil et al., 2016) proposed that medial temporal regions of the DMN drive the activation and variability of spontaneous thoughts. That is, the medial temporal lobes contribute to the diversity of mind wandering content by means of reactivating old thoughts and memories, or by generating novel combinations of thoughts and memories. Once thoughts are generated, other networks such as the salience network and FPCN come online to constrain and modulate thought flow (Christoff et al., 2016). The salience network, comprised of the anterior insula and ACC, has been associated with identifying personally relevant and salient information (Seeley et al., 2007). In terms of mind wandering, the salience network may function as a network that couples with the DMN or FPCN to shift attention to either internally-directed or externally-directed information that is particularly relevant (Christoff et al., 2016).

1.6 Pupillometry as an Index of Attention Fluctuations

In the past few years, a growing interest has emerged in using pupil diameter as a covert indicator of attention lapses and mind wandering. This interest has stemmed from evidence that suggests that pupil diameter covaries with locus coeruleus (LC) activity, even in the absence of external stimuli (Joshi, Li, Kalwani, & Gold, 2016). Although the mechanisms driving this relationship are still under investigation (Costa & Rudebek, 2016), an important consequence of LC activity is the release of norepinephrine (NE) throughout the brain. NE influences both excitatory and inhibitory signals and can modulate the overall gain of neurons (Joshi et al., 2016). Furthermore, the relationship of the LC-NE system and cognitive function can be interpreted in the context of adaptive gain theory (Aston-Jones & Cohen, 2005). Here, two stages of LC activity exist: 1) a phasic stage, in which LC exhibits increases in activity in response to task-related decisions and which drives further focus on the task at hand, and 2) a tonic stage, in which LC exhibits baseline levels of activity that drive disengagement from current tasks and toward alternate activities. The tonic stage is of particular relevance to the proposed project. Following a Yerkes-Dodson relationship, if there is too little tonic LC activity, an individual will be in an unaroused state and demonstrate poor behavioral performance. If there is too much tonic LC activity, the individual will be in an overly aroused state in which hypervigilance and increased attention can lead the individual to distraction and poor behavioral performance (Aston-Jones & Cohen, 2005).

Because the LC-NE system has been linked to pupil diameter, measurements of pupil diameter may serve as a potential covert index of physiological arousal and fluctuations in attention (Kahneman, 1973). Previous research has documented that decreased tonic LC firing is associated with drowsiness and poor attention. Excess tonic LC firing is also detrimental to performance (Lenartowicz, Simpson, & Cohen, 2013). Other research has examined the hypothesis that pupil diameter can relate to attention fluctuations as indicated by self-reports of mind wandering. In one study (Franklin, Broadway, Mrazek, Smallwood, & Schooler, 2016), participants read passages one word at a time and were probed periodically regarding the focus of their attention. The researchers observed increased pupil diameter during a period of 10 seconds preceding self-reports of mind wandering compared to on-task. In a set of experiments, Smallwood and colleagues (2011) found that pupil diameter was larger preceding incorrect responses to working memory probes than correct responses. The researchers also documented greater pupil diameter during the performance of a simple choice response task compared to a demanding working memory task. Smallwood and colleagues confirmed in a second experiment using experience sampling that participants were more likely to mind wander during the choice response task. They proposed that the combination of the two experiments suggests that pupil diameter measurements may reflect periods of mind wandering.

Recently, Unsworth and Robison (2016) examined pupil diameter in response to attention lapses while participants performed a sustained attention task in which they focused on a row of zeros on a computer screen and pressed a button as soon as the values started increasing. Intermittently, the researchers probed participants regarding their focus of attention. Unsworth and Robison noted that baseline pupil diameter varied based on the type of self-reported attention state. In general, pupil diameters preceding on-task trials did not differ from normalized mean pretrial baseline diameter. However, external distraction was associated with large increases in baseline pupil diameter, and mind wandering was associated with smaller baseline pupil diameters compared to on-task self-reports. These important findings indicate that different attention lapses can be associated with differences in pupil diameter measurements. However, these findings contradict the research described above that suggests mind wandering is associated with increased baseline pupil diameter (Franklin et al., 2016, Smallwood et al., 2011, Smallwood et al., 2012). By building on the advantages of the MRT procedure and the range of attention states probed during experience sampling, another goal of the current research is to more clearly delineate the relationship between pupil diameter and attention lapses.

1.7 Attention Lapses and Performance

Recently, continuous performance tasks have been used to examine behavioral and neural markers in mind wandering and attention more generally. Through these tasks, researchers have been able to assess more granularly the role of the DMN and other brain networks during fluctuations in performance and off-task attention states. Esterman, Noonan, Rosenberg, and DeGutis (2012) administered a continuous performance task during fMRI scanning and examined variability in RT across trials and commission errors to targets. As expected, they observed increased DMN activity preceding lapses to targets and increased dorsal attention network (DAN) activity preceding correct responses to targets. The DAN is a network comprised of superior parietal regions and the frontal eye fields, and has been consistently linked with attending and responding to external task demands (Dixon, Andrews-Hanna, Spreng, Irving, & Christoff, 2016). Interestingly, DMN activity increased during periods of low variability RT ("in the zone" performance) and decreased during periods of high variability RT ("out of the zone" performance). Furthermore, when participants made commission errors during in the zone performance, there was increased DMN activity compared to correct trials that occurred in the zone. Yet when participants made commission errors during out of the zone performance, there was decreased DAN activity compared to correct trials, and no changes in DMN activity. Esterman and colleagues proposed that the increased DMN activity during in the zone performance may reflect efficient, automatized performance of the task. A moderate amount of DMN activity may be beneficial to maintain task performance, yet substantial increases may prove to be detrimental.

Another example of the neural mechanisms of continuous performance comes from Kucyi, Hove, Esterman, Hutchison, and Valera (2016b). They examined behavioral tapping variability during fMRI acquisition and observed increased activation in the DMN and insula during low-variability, "in the zone" performance whereas activation in the DAN and salience network increased during high-variability, "out of the zone" performance. Kucyi and colleagues proposed an explanation similar to that of Esterman and colleagues (2012): A moderate amount of DMN activation may be beneficial for supporting performance of these types of continuous, attention-demanding tasks in an efficient manner.

However, neither Esterman et al. (2012) nor Kucyi et al. (2016b) were able to tie their results directly to the implications of mind wandering and address how increased DMN could support both stable performance and off-task thought. To address this limitation, Kucyi and colleagues (2016a) examined mind wandering reports and behavioral performance simultaneously during fMRI. Here, participants performed the gradCPT. This task consisted of viewing gradually changing images of scenes. Participants were instructed to press a button for each city scene and withhold the button press for each mountain scene. After each block, participants rated the extent to which they were on-task or were mind wandering. When examining DMN activation preceding the thought prompts, Kucyi et al. (2016a) found independent, additive effects of self-report and RT variability. Overall, mind wandering was associated with greater RT variability. However, DMN activity was highest during off-task attention with stable RT, whereas DMN activity was lowest during on-task attention with variable RT. Kucyi et al. discussed potential interpretations of these findings and speculated that DMN activity may be driven by separate neurophysiological processes. For example, mind wandering may be time-locked to increases in DMN activation whereas decreases in DMN deactivation support stable behavior. Kucyi and colleagues further suggested that the relationship between variable behavior and decreased DMN activity could arise due to periods of perceived increases in cognitive demand, in which DMN deactivation increases. Although these interpretations are speculative, the findings from Kucyi et al. indicate that the relationship between performance and attention state is complex. Simultaneous consideration of both self-reported mind-wandering and behavior could yield insights into the function of the DMN and other brain networks (Kucyi et al., 2016a). In the current research, a similar approach is taken with the MRT procedure to examine brain activity during stable and variable performance in both on-task and off-task attention states.

1.8 Current Research and Hypotheses

Research in attention and mind wandering has evolved dramatically over the recent years. Whereas previous research posited that mind wandering was merely spontaneous, unintentional thought driven mainly by the DMN, emerging studies using multimodal approaches and triangulation have revealed that mind wandering and related thought processes are complex and dynamic, driven by networks of interacting brain regions and with differing implications in performance. In addition, new theories and frameworks have been developed for these processes. With these, new questions arise that aim to elucidate the mechanisms and implications of mind wandering.

The objective of this current work was to overcome the limitations of previous research that has dichotomized attention states as on-task and off-task and examine the behavioral and neural characteristics across a broad range of attention states and their dynamics by using a set of multimodal cognitive neuroscience methods. In addition, by isolating the characteristics of each attention state, this approach aims to provide a clearer understanding of off-task thoughts relative to on-task thought and other forms of attention lapses. My first goal addressed the replication and extension of previous research, where I further characterized the behavioral and neural correlates of a range of attention lapses using behavioral performance variability, fMRI, and pupillometry. Whereas numerous previous studies have documented increased DMN activation during off-task attention states compared to on-task states (e.g., Christoff et al., 2009), it is less clear how brain activity varies across other distraction states such as task-related interference and inattentiveness. Furthermore, Christoff et al. (2016) proposed sets of brain networks involved in the dynamics of thought, including spontaneous and constrained thought, however this has not yet been empirically investigated. Here, brain activation and functional connectivity within and between the DMN and FPCN were measured to examine the relative roles of each network in the dynamics of thought.

In addition, pupil diameter has been associated with changes in attention state, but different studies have reported opposite findings regarding mind wandering and pupil diameter (e.g., Unsworth and Robison (2016) and Smallwood et al. (2011)). Unlike the sustained attention task of Unsworth and Robison (2016) and the choice response and working memory tasks of Smallwood et al. (2011), the MRT does not have a series of punctate stimulus presentations and response selection requirements that could affect event-related, phasic pupil diameter responses over and above attention fluctuations themselves. Therefore, the aim of this procedure was to provide a more fundamental approach to examining how tonic pupil diameter indexes fluctuations in attention, with the prediction that pupil diameter differentially corresponds to self-reported attention states. Furthermore, it may be possible that neural and pupillometric measures can distinguish different self-reported attention states, even if behavior does not. This would be an important contribution to understanding the subtleties of how different attention states are implemented in the brain.

Regarding behavioral performance, it was predicted that, as in previous research (Seli et al., 2013), RRT variability would be increased during the off-task attention state. However, the implications of the other attention states on performance, and the extent to which these attention states differentially affect performance, is not clear. One of the goals here was to directly document and compare RRT variability across these different attention states. Although reaction time and related performance metrics (e.g., RRT) are fundamental measurements in cognitive psychology research, they are not without their limitations. These metrics typically follow an ex-Gaussian distribution, where a greater number of larger RTs or RT variances skew the distribution positively (Heathcote, Popiel, & Mewhort, 1991). However, the extent to which a sample of performance data follows this distribution can provide an interesting perspective into the mechanisms governing each instance of performance (Schmiedek, Oberaurer, Wilhelm, Sub, & Wittmann, 2007). Therefore, to obtain further insight into behavioral performance across attention states, ex-Gaussian parameters (*mu*, *sigma*, and *tau*) were estimated from the raw RRT values for the attention states in the first thought-prompt (on-task, TRI, off-task, and inattentive).

The next goal here was to test the extent that performance and self-reported attention state are dissociable. Although the majority of research has documented congruency between poor performance and off-task attention states (e.g., Christoff et al., 2009), this is not always the case (e.g., Henriquez et al., 2016). In general, it is likely that across mind wandering episodes, there are instances of good performance and poor performance. Similarly, across periods of on-task attention states, there are instances of both good and poor performance. However, the neural mechanisms that guide strong performance during periods of distraction and which diminish performance during periods of focus are not clear. Recently, as described above, Kucyi et al. (2016a) demonstrated that RT variability and self-reported attention provided independent, additive effects in predicted DMN activation. The current work addressed this topic in a manner similar to Kucyi et al. (2016a). The analysis focused on the on-task and off-task reports from the first prompt and divided the trials into high and low performance variability (e.g., Esterman et al., 2012) to conduct a quadrant state analysis (Figure 1).

		performance	
		low variability	high variability
attention state	on-task	on-low	on-high
	off-task	off-low	off-high

Figure 1 – The quadrant state analysis approach

Although the task in Study 1 remained constant, as discussed in Kucyi et al. (2016a), it was possible that there were "perceived" transient changes in cognitive demand across continuous performance tasks. To guide analysis, a set of hypothesized characteristics of each of the four quadrant states was organized based on potential variations in cognitive demand across the task. The instances where participants reported being on-task and were able to maintain focus to perform the MRT with low variability (Figure 1: on-low) were considered to reflect the "in the zone" epochs of Esterman and colleagues (2012) and Kucyi and colleagues (2016a), or a general "on-task" state. As in previous research (Esterman et al., 2012), a moderate amount of DMN activation was expected to support these processes. Conversely, instances where mind wandering was associated with increased variability in tapping performance (Seli et al., 2013; Figure 1: off-high) were considered to be periods of time where participants perceived the task as challenging, but they had disengaged from the task and shifted their attention to other matters of concern. (It would be unclear from the current procedure the extent to which individuals first perceived the task as challenging and then broke into mind wandering, or whether the task became challenging because of a decrease in attention to the task.) In these instances, increased DMN activation relative to the on-low condition was expected. It is less clear the implications of reporting off-task thoughts during periods of low variability (Figure 1: off-low). It is possible that these instances were similar to other cases noted in the literature in which individuals could mind wander in the presence of undemanding tasks (Godwin et al., 2017; Smallwood & Schooler, 2015). Here, it was predicted that mind wandering would be driven by both FPCN and DMN regions (Smallwood & Schooler, 2015). Finally, there was the possibility that high performance variability would be identified during on-task reports (Figure 1: on-high). It is unclear what this would indicate, however one possibility is that these instances could reflect attempts at re-focusing attention to the task at hand. This may be similar to the stages in mind wandering proposed by Hasenkamp and colleagues (2012) in which individuals noticed they were off-task and attempted to shift their attention back on track. Behavioral variability may have indicated that the individual was "off-task", but the individual may have reported being on-task as he or she attempted to regain focus by thinking about the task. From this perspective, increased activation in the salience network was predicted (Hasenkamp et al., 2012; Kucyi et al., 2016a).

Finally, a remaining goal was to examine the effect of cognitive load on performance and the types of attention states one experiences when under different levels of load. Although previous research suggests that mind wandering decreases under increased load (Seli et al., 2018b), this is not always the case (e.g., Feng, D'Mello, & Graesser, 2013). In addition, it was less certain the extent to which other forms of distraction are experienced across cognitive load levels. By directly manipulating task difficulty in Study 2, I was able to examine this. Furthermore, the context regulation hypothesis (Smallwood & Andrews-Hanna, 2013) generates some interesting predictions regarding the dynamics of thought as a function of cognitive load. For example, if constrained thoughts are largely supported by executive function and the FPCN as proposed by Christoff et al. (2016), then these thoughts should occur more frequently during easy tasks with low cognitive load. Conversely, if spontaneous thoughts are driven by the DMN and medial temporal lobe regions and are relatively independent of executive function, then they may occur equally across difficulty levels, or be relatively more frequent in difficult task conditions. More specific predictions can be made regarding task performance depending on the attention state and task level. For example, when constrained thoughts are observed under increased demand, there could be corresponding decreases in performance due to the inability of executive function to optimally guide both processes. Answering these questions would provide additional empirical evidence for the framework proposed by Christoff and colleagues (2016) and further understanding of the role of task difficulty in mind wandering.

CHAPTER 2. STUDY 1

2.1 Method

2.1.1 Participants

A total of 35 participants (17 female, 17 male, 1 no response) were recruited from the Georgia Institute of Technology. Due to technical difficulties with the MRI scanner, the datasets from the first two participants were excluded. Two additional participants were excluded due to scanner contraindications. Therefore, 31 participants were included in behavioral and MRI analyses. The age of participants ranged from 18 to 23 (M = 20, SD = 1.6). All participants were right-handed, had normal or corrected-to-normal vision, and were not contraindicated for the scanner. In addition, eye tracking datasets were collected from a subset of these participants (n = 24) and were included in pupil diameter analysis.

2.1.2 Metronome Response Task

Participants were instructed to keep their eyes open and focus on a fixation in the center of the screen. Participants performed the MRT across a series of tap periods. For each tap period, participants were instructed to tap along as synchronously as possible to a metronome sound. The metronome tone consisted of a 450-Hz sine wave presented for 75 ms (following parameters of Kucyi et al., 2016b and Seli et al., 2013). Each metronome tone was preceded by 650 ms of silence and followed by 575 ms of silence (following the MRT procedures of Seli et al.). Thus, across the tap periods the metronome sounded at a rate of approximately .77 Hz (one tone per 1300 s). Each tap period was preceded by a short baseline fixation with a 2 – 4 s variable duration. The fixation cross remained on the screen across the duration of the tap periods. Participants had a 4-button response box and were instructed to tap by pressing the button under their right index finger. After each tap period ended, the metronome stopped and participants were presented with the thought probes.

2.1.3 Thought Probes

Participants were presented with a set of thought probes at the end of each tap period that asked them to classify the attention state they were in just prior to the onset of the probe. The first thought probe followed those from Stawarczyk et al. (2011) and Unsworth and Robison (2016): 1) on-task, 2) task-related thoughts, 3) off-task, and 4) not alert / drowsy. Participants had 6 s to select their response via button-press. After selecting the response, the prompt remained on the screen until the end of the 6 s, and participants could change their response if desired.

Following the first prompt, if participants did not select the off-task option, they were then presented with a fixation for the next 10 s. If participants selected the off-task option, they were then presented with two additional prompts to further address the nature of off-task thought. The second prompt addressed the environmental nature of the off-task thought: 1) surrounding environment, 2) internal thoughts. The third prompt addressed the dynamics of thought, following theorizing by Christoff et al. (2016) and Mills et al. (2018): 1) freely moving, 2) constrained. Each of these prompts was presented for an additional 5 s and remained on the screen for the full length of time.

2.1.4 Eye Tracking

Pupil diameter was measured during the main experiment with an EyeLink 1000 Plus MRI-compatible eye tracker. Eye tracking data was sampled at a rate of 1000 Hz. A 5-point calibration was performed at the start of the first run, and a validation procedure was performed at the start of the subsequent four blocks.

2.1.5 fMRI Design

Imaging was conducted on a Siemens 3T Trio MRI scanner at the Georgia Institute of Technology. All participants completed a T1-weighted MPRAGE anatomical scan with the following acquisition parameters: FoV = 256 mm; 176 slices; 1.0 x 1.0 x 1.0 mm^3 voxels; flip angle = 9˚, TE = 3.98 ms; TR = 2250 ms; TI = 850 ms.

Participants then completed the main experiment over the course of five runs (run duration = 10 min, 33 s). During each run, functional T2*-weighted echo-planar scans were collected with the following acquisition parameters: FoV = 204 mm; slices = 37; 3.0 x 3.0 x 3.0 mm^3 voxels; interleaved slice acquisition; gap = 0.5 mm; flip angle = 90˚; TE = 30 ms; TR = 2000 ms.

2.1.6 Experimental Procedure

The MRT was run using E-Prime software. All visual stimuli were presented in white font on a black background. In order to familiarize participants with the MRT, a practice session was held outside the scanner before the main experiment began. The experimenter explained the meaning of each thought probe category and provided examples as needed

(Appendix A). The participants then performed five trials at a desktop computer to become familiar with the act of tapping and reporting attention states.

The main experiment consisted of five runs of 15 tap periods per run. At the start of each tap period, participants focused on a fixation cross in the center of the screen. This fixation served as the baseline with a variable duration (2 – 4 s). Following the baseline, the fixation remained on the screen and the metronome started to sound. Participants were instructed to begin tapping as soon as they heard the metronome and to tap along as synchronously as possible for the duration of the tap period. The duration of the tap periods varied and the number of tap periods of each duration followed approximately an exponential distribution and ranged as follows for each block: six tap periods of 16 s; three tap periods of 20 s; two tap periods of 24 s; two tap periods of 28 s; one tap period of 32 s; and one tap period of 36 s. The order in which these tap periods occurred within each block was randomized. The exponential distribution of tap period durations was used to minimize expectancy effects from participants. At the end of the tap period, participants were presented with the first thought probe and had 6 s to enter their response. If participants selected the "off-task" option, they were then presented with two additional thought probes (described under "Thought Probes"). If participants selected any of the other three options, they were presented with a 10-s fixation period until the next baseline and tap period began. This fixation period was included to equate the duration of the entire probe period, regardless of the selection participants made to the first prompt. Upon completion of the main experiment, participants completed a questionnaire regarding their experience during the study.

2.1.7 Data Processing and Analysis

All behavioral, fMRI, and pupillometry analyses are based on the data of the last 5 to 10 s preceding the thought probes. This duration is similar to that of other mind wandering studies using experience sampling during fMRI (Christoff et al., 2009) and should reliably capture the behavioral and neural correlates of attention fluctuations. In addition, all analyses required that each cell contain a minimum of two reports per participant. Cells with only one report per participant were excluded from the respective analysis. Unless otherwise noted, all behavioral and pupillometric inferential statistics were computed using linear mixed-effects models with the *lme* function from the *nlme* package in R. Linear mixed-effects models are extensions of the general linear model, and both fixed and random effects are modeled. These models have the advantage of being able to handle unbalanced designs and missing cells and have previously been used in mind wandering research to address these concerns (Unsworth & Robison, 2016). Post-hoc comparisons with Tukey correction were run using the *glht* function from the *multcomp* package in R.

Preprocessing and Analysis of Behavioral Data. All behavioral analyses were conducted on the performance data from the last five metronome tones preceding the thought prompts (Seli et al., 2013); this makes up approximately the last 6.5 s of the tapping period. Before statistical analysis, performance accuracy was calculated for these five taps preceding each tapping period. All missing and incorrect taps were counted as errors. To be included in analysis, each trial needed to have at least three correctly performed taps out of the five total. With these exclusion criteria, an average of 3.53% (*SEM* = 1.39%) of trials were removed from each participant's data.

The steps for behavioral data analysis of the MRT followed the procedures of Seli and colleagues (2013). For each participant for each tap period, the RRT was calculated from the last five metronome tones. The RRT was obtained by calculating the difference between the onset of the metronome tone and the corresponding time of key press. From here, the RRT variance was calculated from these values. Because the distribution of RRT variance is typically skewed right, a natural log transformation was applied to these values (Seli and colleagues, 2013). Transformed RRT variance served as the dependent variable in the behavioral data analysis.

The frequency of each attention state in Prompt 1 was calculated as a proportion out of all valid trials. Because Prompts 2 and 3 are nested within the off-task response of Prompt 1, the frequency of each attention state from these prompts was calculated as a proportion out of all valid off-task trials. The arcsine transformation (defined as $sin^{-}1\sqrt{p}$ where p is the proportion) was applied to all proportion values before running inferential statistics. For interpretability, all descriptive statistics and figures depict the raw values.

Ex-Gaussian Behavioral Analysis. Reaction time data typically follow an ex-Gaussian distribution. This analysis examined the extent to which RRT variability followed an ex-Gaussian distribution and whether the distribution parameters varied across attention states in the first prompt. Ex-Gaussian parameter estimation was performed using the *timefit* function with bootstrapping (1000 samples) in the R package *retimes*. This function performs parameter estimation for reaction time distributions using the maximum likelihood method. For each participant, raw RRT variance was modeled separately for each of the four attention states. Specifically, for each condition, the raw RRT variance was calculated for each trial and passed to the *timefit* function. Ex-Gaussian distribution parameters (*mu*, *sigma*, and *tau*) were estimated for that condition. For each participant, one estimate was obtained for each parameter for each condition. From these estimates, a linear-mixed effects analysis was run at the group level to test whether these parameters (and hence, the ex-Gaussian distribution) differed across attention states.

Preprocessing and Analysis of Pupillometric Data. Analysis was performed on epochs of the last 5 s of pupil data preceding the thought prompts along with the 2 – 4 s baseline period at the start of each tapping period. Epochs were excluded from analysis if missing pupillometry data was greater than 40% of the epoch (Smallwood et al., 2011). Missing data points in included epochs were linearly interpolated to create complete time series of pupil diameter measures. Then, epochs were filtered using a Hampel filter with a window-length of 7 (run in R with the package *pracma*). This function applied a moving window to each time series in order to detect local outliers via median absolute deviation. Values detected as outliers were replaced with the median of the moving window.

Each epoch was baseline-corrected by dividing the time series by the median pupil diameter of the corresponding baseline epoch. The baseline-corrected epoch time series were then averaged to provide mean pupil diameter measures for each thought prompt. Therefore, values greater than one indicate an increase in pupil diameter relative to baseline, and values less than one indicate a decrease. (For interpretability, figures depict baseline at y = 0.) Mean pupil diameter was analyzed within each prompt.

Preprocessing and Analysis of fMRI Data. Data preprocessing was performed using Analysis of Functional NeuroImages (AFNI). Standard preprocessing was conducted, including despiking, slice time correction, motion correction, spatial smoothing

(FWHM of 6.0 mm), structural-functional alignment, and normalization to MNI space. Individual analysis was conducted using AFNI. Group level analyses were conducted using AFNI and custom scripts in MATLAB. Individual and group analyses were conducted separately for each of the three prompts.

Individual Analysis. Design matrices were created for each participant with covariates for each attention state. For Prompt 1, covariates of interest were on-task, TRI, off-task, and inattentive states. For Prompt 2, covariates of interest were external and internal states. For Prompt 3, covariates of interest were spontaneous and constrained states. For all analyses, covariates of no interest consisted of trials with no/incorrect responses, the probe period when participants reported their attention states, and the fixation period at the start of each tapping period. For each analysis, the last 5.2 seconds (corresponding to the last four taps) preceding the thought prompt were convolved with an idealized hemodynamic response function and modeled with a generalized linear model in AFNI.

Whole-Brain Group Analysis. Data were analyzed at the group level with a linear mixed-effects model using the 3dLME function in AFNI. Like with the behavioral analyses, this model is an alternative to the traditional ANOVA but includes a random intercept and allows for missing data. The 3dLME function uses the coefficients modeled for each variable of interest in the individual analysis. Group-level general linear tests were run for the following contrasts from Prompt 1: on-task vs all distraction states; on-task vs TRI; on-task vs off-task; on-task vs inattentive; TRI vs off-task; TRI vs inattentive; and off-task vs inattentive. In addition, two conjunction analyses were run to further isolate neural activity pertaining to individual distraction states in Prompt 1. The first analysis tested which voxels were significant in both the off-task and inattentive states compared to the on-task state (off-task > on-task ∩ inattentive > on-task). The second analysis tested which voxels were significant in the off-task state compared to both the inattentive and on-task conditions (off-task > on-task ∩ off-task > inattentive). For Prompt 2, a general linear test was run for the contrast internal vs external. For Prompt 3, a general linear test was run for the contrast spontaneous vs constrained. A threshold of FDR corrected q = .05 was set for statistical analyses.

Quadrant State Analysis. A separate individual and group analysis was conducted for the quadrant state analysis. Data were analyzed in the same manner as described for the three prompts. The trials from the upper and lower third of behavioral performance from on-task and off-task attention states were included in analysis. Design matrices were created for each participant with covariates for on-high, on-low, off-high, and off-low. Covariates of no interest were included for the other two attention states (task-related interference and inattention) along with the on-task and off-task trials not included in this analysis. In addition, covariates of no interest were created for trials with no/incorrect responses, the probe period when participants reported their attention states, and the fixation period at the start of each tapping period.

The group-level analysis was performed using 3dLME. General linear tests were run for the following contrasts: on-low vs on-high; off-low vs off-high; on-low vs off-low; and on-high vs off-high. In addition, student t-tests were run to test the last two contrasts, on-high vs off-low, and on-low vs off-high, as these could not be implemented with the 3dLME syntax. A threshold of FDR corrected q = .05 was set for statistical analyses.

Previous research (Kucyi et al., 2016a) found independent contributions of attention state and behavioral performance to BOLD signal in the DMN. Therefore, to directly test for this effect in the current study, percent signal change was examined between each condition in the DMN. The DMN here was defined *a priori* based on the 7-network estimate parcellation from Yeo et al. (2011). A mask was then used to extract the average beta coefficients generated for each condition. At the group level, a 2x2 linear mixed effects model was run in R to test the effect of performance and attention with DMN percent signal change as the dependent variable.

Functional Connectivity Analysis. A seed-based, beta-series functional connectivity analysis (Rissman, Gazzaley, & D'Esposito, 2004) was conducted to more closely examine the neural correlates of the dynamics of thought measured with Prompt 3. Individual GLM analyses were run for each participant following procedures described above, with the addition that the trials from the constrained and spontaneous attention states were modeled individually. Analysis was based on a set of ROIs comprising the DMN and FPCN taken from previous literature (Godwin et al. (2017) and Spreng et al. (2013)). There were 17 nodes in the DMN and 15 nodes in the FPCN, and each node was a 5-mm spherical ROI. For each participant, the time series of individual beta estimates were averaged across the voxels for each node to create one average beta series per node per attention state. The left hippocampus and left dlPFC served as the seed regions for the DMN and FPCN, respectively. The hippocampus was selected due to its role within the DMN as a source of off-task thought content (Christoff et al., 2016); the left side was selected arbitrarily. The dlPFC was selected because of its prominent role in the FPCN (Christoff et al., 2016) and its vast implications in directed task processing in general. Again, the left side was selected arbitrarily. Each seed region's average beta series was then correlated with each node's average beta series. For both the DMN and FPCN, the group mean fisher-transformed correlation coefficients from the spontaneous and constrained attention states were statistically tested 1) against zero (within-state analysis) 2) against each other (across-state analysis).

A second functional connectivity analysis was conducted to examine large-scale network connectivity during spontaneous and constrained thought. Connectivity matrices were calculated from the mean beta series of each node. Following previously published procedures (Godwin et al., 2017), within-network functional connectivity was calculated for the DMN and FPCN by taking the triangular half of the correlation matrix of all nodes for each network. The average of these fisher-transformed correlation coefficients was used as the measure of within-network connectivity. Between-network functional connectivity was calculated by correlating all DMN nodes with all FPCN nodes and averaging the fisher-transformed correlation coefficients.

2.2 Results

2.2.1 Self-Report Measures

Prompt 1. The proportions of each reported attention state collapsed across blocks are shown in Figure 2. Overall, off-task thoughts were most frequent and inattentive states were least frequent. To test for significant differences between proportions, a linear mixed-effects model was run with Prompt 1 as a factor and the four attention states from Prompt 1 as the levels. There was a significant main effect of attention state, $F(3,90) = 9.34$, $p < .001$. Post-hoc comparisons indicated that there was a significantly smaller proportion of inattentive states (M = .15, SEM = .02) compared to on-task (M = .25, SEM = .03; z = -3.00, p = .014), TRI (M = .27, SEM = .02; z = -3.80, p < .001), and off-task (M = .32, SEM = .03; z = -5.20, p < .001). No other comparisons were significant, .79 < all zs < 2.20, all ps > .17. In general, participants reported that their attention state was typically focused on something, whether it was on the task, TRI, or off-task thoughts. These attention states were reported relatively equally and more frequently compared to the inattentive state.

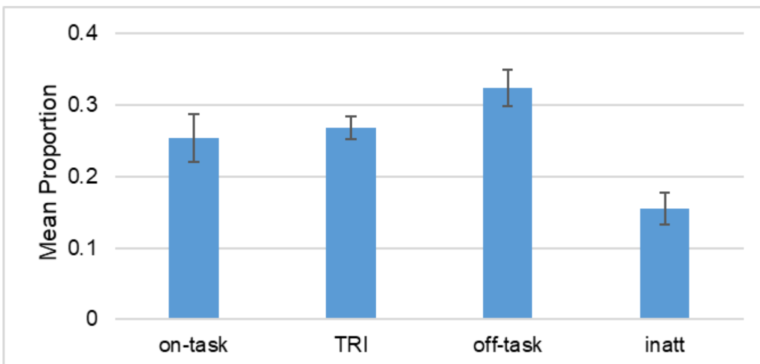

Figure 2 – Proportion of each attention state in Prompt 1. There was a main effect of attention state, and significantly fewer inattentive states reported compared to the other states.

The proportions of each attention state by block are shown in Figure 3. Across blocks, the inattentive state was reported relatively less frequently than the other attention states. In addition, there was a small increase in frequency of the off-task state across the five blocks. To test for significant differences as a function of block, a 2x2 linear mixed-effects model was run with Prompt 1 and block as factors. However, there was no significant main effect of block, $F(4, 570) = .098$, p = .983, nor a significant interaction, $F(12, 570) = 1.392$, p = .165. As described above, there was a significant main effect across the attention states of Prompt 1, $F(3, 570) = 29.168$, p < .001.

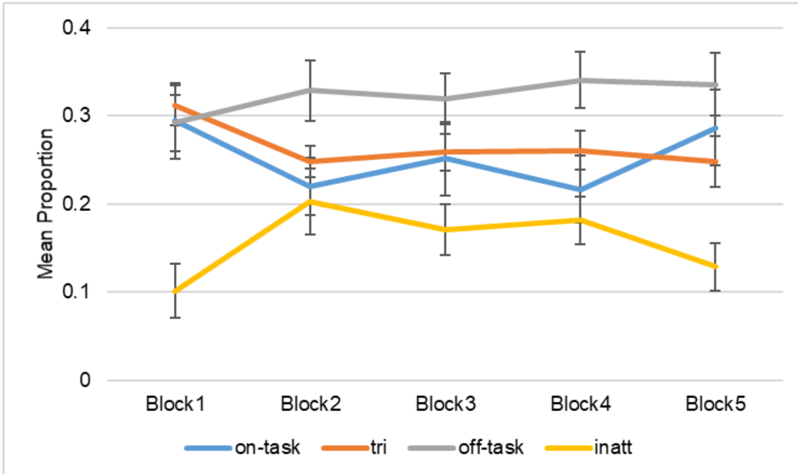

Figure 3 – Proportion of each attention state in Prompt 1 by block. The proportions of each attention state were calculated from the number of all attention states per block.

Prompt 2. The proportions of each attention state response collapsed across blocks are shown in Figure 4. Overall, more internal (M = .66, SEM = .03) than external (M = .34, SEM = .03) thoughts were reported. This comparison was significant, $t(30) = -4.77$, $p < .001$.

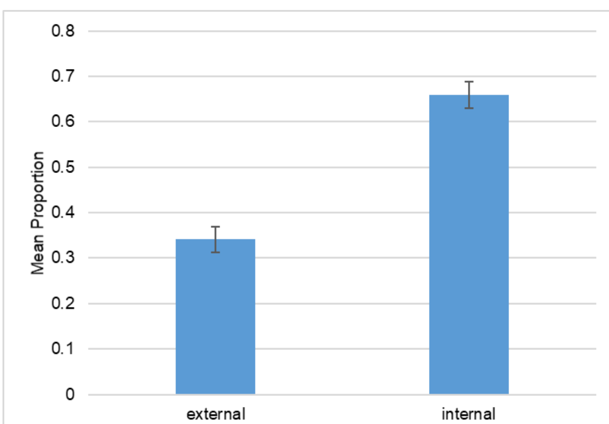

Figure 4 – Proportion of external and internal attention states calculated out of all off-task thoughts. There were significantly more internal than external thoughts reported.

The proportions of internal and external attention states across blocks are shown in Figure 5. To test for significant differences between attention states in each block, paired t-tests were run on the proportions of reported internal and external attention states within each block for a total of five comparisons. Bonferroni correction was applied. There were on average more internal than external thoughts reported in Blocks 1 and 2, however the difference in proportions within the first two blocks did not quite reach significance (Block 1: $t(29) = -1.946$, $p = .061$; Block 2: $t(29) = -1.876$, $p = .071$). However, the difference between proportions of internal and external thoughts within the last three blocks all reached significance after correcting for multiple comparisons, all $|t|$s > 3, all ps < .002.

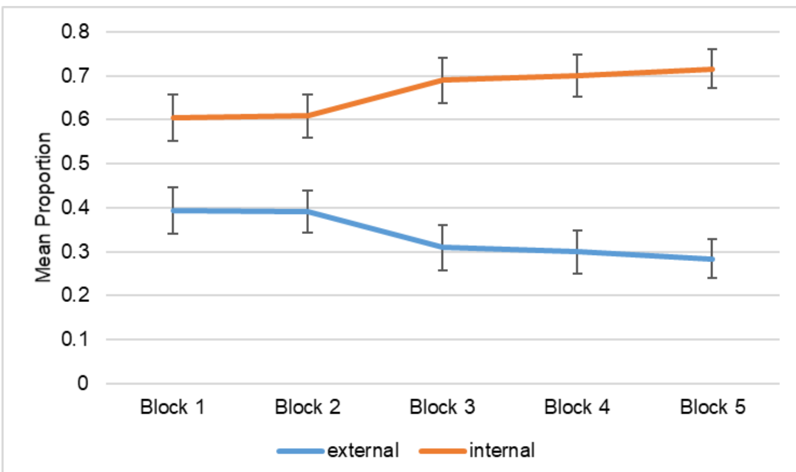

Figure 5 – Proportion of external and internal attention states by block. Proportions were calculated out of the total number of off-task thoughts in each block. Over the course of the last three blocks there were significantly more internal than external thoughts reported.

Prompt 3. The proportions of each attention state collapsed across blocks are shown in Figure 6. Overall, more spontaneous ($M = .61$, $SEM = .03$) than constrained ($M = .39$, $SEM = .03$) thoughts were reported. This comparison was significant, $t(30) = 3.38$, $p = .002$.

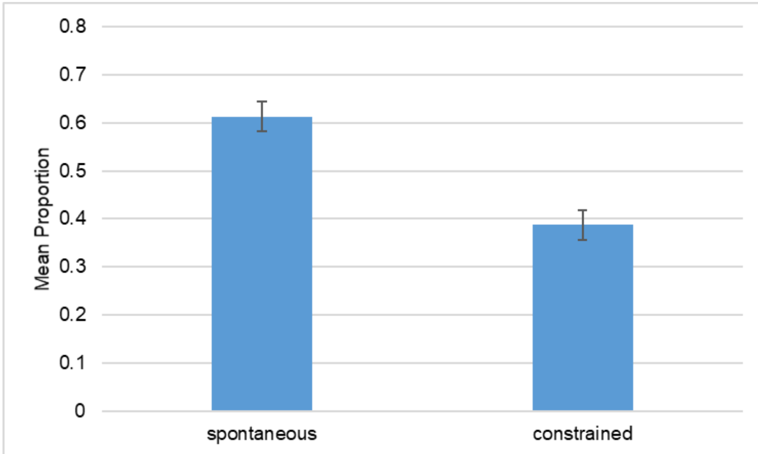

Figure 6 – Proportion of spontaneous and constrained attention states calculated out of all off-task thoughts. There were significantly more spontaneous than constrained thoughts reported.

The proportions of spontaneous and constrained attention states across blocks are shown in Figure 7. As with Prompt 2, a set of paired t-tests was run to test for significant differences between these proportions within each block. There was a significant difference between the proportion of spontaneous and constrained thoughts in Block 1, $t(28) = 2.855$, $p = .008$, and Block 3, $t(28) = 3.607$, $p = .001$. The other blocks were not significant, however moderate trends appeared in each comparison, $1.68 <$ all ts < 2.01 and $.051 <$ all ps $< .103$. Bonferroni correction for the five comparisons was applied.

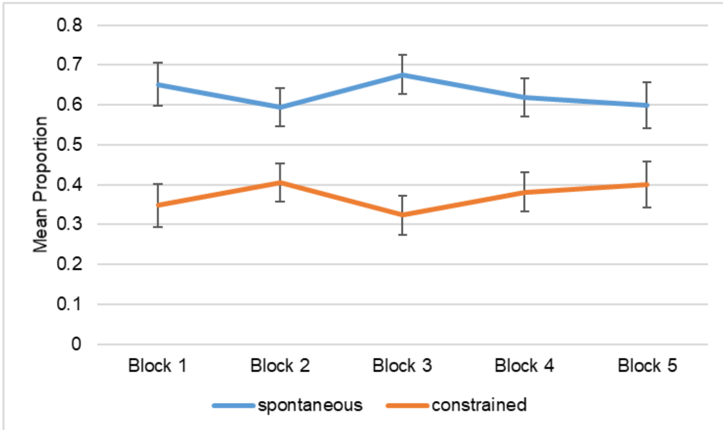

Figure 7 – Proportion of spontaneous and constrained attention states by block. Proportions were calculated out of the total number of off-task thoughts in each block. There were significantly more spontaneous thoughts reported in Block 1 and Block 3, although a trend in the same direction was present across the other blocks.

2.2.2 Behavioral Measures

A linear mixed-effects model was run to examine the effect of block on overall RRT variance. There was a significant main effect of block, $F(4, 120) = 7.01$, $p < .001$ (Figure 8). Results of post-hoc comparisons are summarized in Table 1. In general, RRT variance was lowest in the first block, increased during the next three blocks, and decreased during the final block.

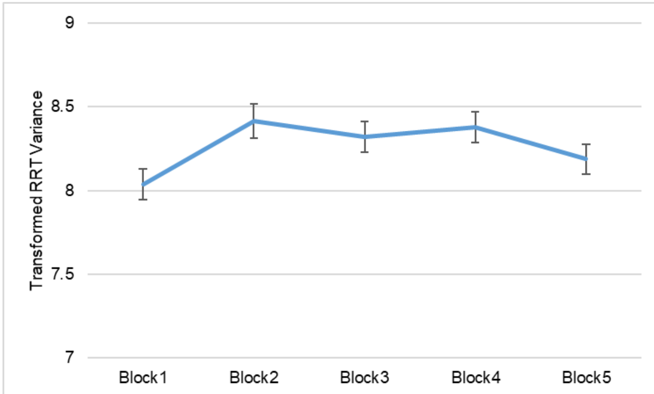

Figure 8 – Mean RRT variance (natural log transformed) across blocks. There was a significant main effect across blocks.

Table 1 – Post-hoc comparisons of mean RRT variance between each block. *: Significant after Tukey multiple comparison correction

Pair		**z**	***p*-value**
Block 1	- Block 2	4.642	< .001 *
	- Block 3	3.470	.005 *
	- Block 4	4.174	< .001 *
	- Block 5	1.844	.348
Block 2	- Block 3	-1.172	.767
	- Block 4	-0.468	.990
	- Block 5	-2.799	.041 *
Block 3	- Block 4	0.704	.956
	- Block 5	-1.627	.480
Block 4	- Block 5	-2.331	.135

Prompt 1. A linear mixed-effects model was run with Prompt 1 as a factor and the four attention states from Prompt 1 as the levels. There was a significant main effect of attention state, $F(3, 83) = 17.78$, $p < .0001$ (Figure 9). Results of post-hoc comparisons are summarized in Table 2. RRT variance was significantly greater during each distraction state compared to being completely on-task. However, most distraction states did not differ significantly from each other in terms of performance variability.

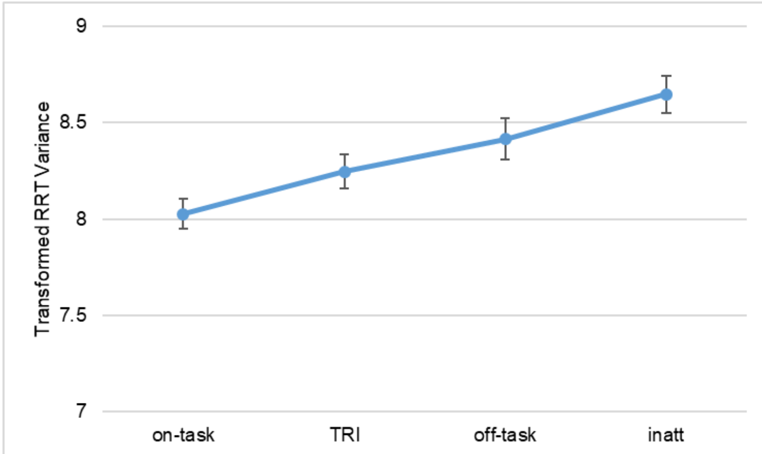

Figure 9 – Mean RRT variance for each attention state in Prompt 1. There was a significant main effect of attention state.

Table 2 - Post-hoc comparisons of RRT variance between each attention state in Prompt 1. *: Significant after Tukey multiple comparison correction.

Pair		**z**	***p*-value**
on-task	- TRI	2.749	.030 *
	- off-task	4.900	<.001 *
	- inattentive	7.084	<.001 *
TRI	- off-task	2.198	.124
	- inattentive	4.585	<.001 *
off-task	- inattentive	2.511	.058

Prompts 2 and 3. To examine the main effects and interactions between environment (external versus internal) and dynamics (spontaneous versus constrained) on performance variability, a 2x2 linear mixed effects model was run. However, there were no significant effects of environmental attention state, $F(1, 62) = .389$, $p = .535$, or dynamic attention state, $F(1, 62) = .985$, $p = .325$. In addition, there was no significant interaction between environmental and dynamic attention states, $F(1, 62) = 2.495$, $p = .119$. Results are shown in Figure 10.

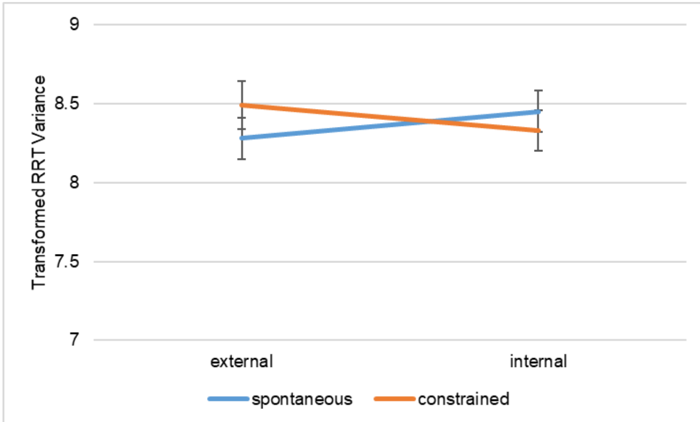

Figure 10 – Mean RRT variance (natural log transformed) for Prompts 2 and 3. There were no significant main effects or interaction.

Ex-Gaussian Analysis. The ex-Gaussian analysis was run on the raw RRT values calculated from the last five taps of each trial. Figure 11 illustrates the results for all three parameters. There was no significant difference in *mu* values across attention states, $F(3, 81) = 1.00$, $p = .40$. There was a marginal significant difference in *sigma* values across attention states, $F(3, 81) = 2.66$, $p = .054$. There was a significant difference in *tau* values across attention states, $F(3, 81) = 7.75$, $p < .001$. Pairwise comparisons for the *tau* parameter analysis are summarized in Table 3. The mean values of the parameters were used to generate probability distribution functions for each attention state. These distributions are shown in Figure 12.

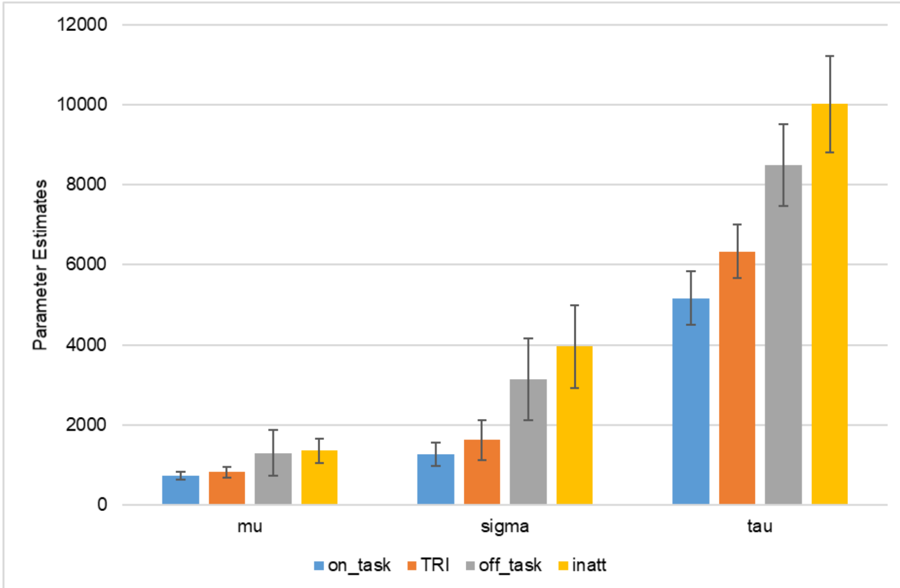

Figure 11 – Mean parameter estimates from the ex-Gaussian analysis of raw RRT variance in Prompt 1. Statistical analyses were run separately for each parameter. There was a significant main effect of attention state for the *tau* parameter.

Table 3 - Post-hoc comparisons of the *tau* parameter between attention states of Prompt 1. *: Significant after Tukey multiple comparison correction.

Pair		**z**	***p*-value**
on-task	- TRI	1.270	.582
	- off-task	3.565	.002 *
	- inattentive	4.285	<.001 *
TRI	- off-task	2.343	.088
	- inattentive	3.177	.008 *
off-task	- inattentive	1.019	.738

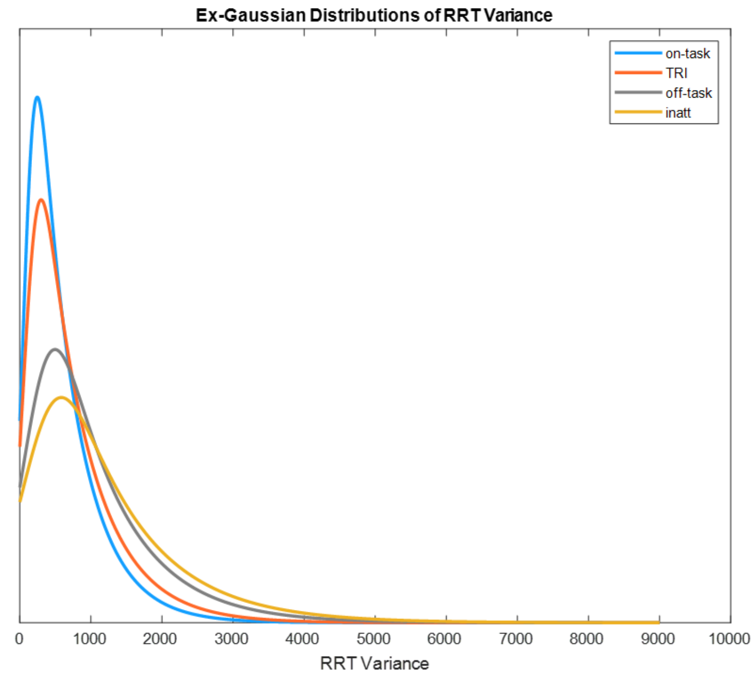

Figure 12 – Distribution functions generated from the average ex-Gaussian parameters of each attention state.

Quadrant State Analysis. Analysis focused on the on-task and off-task reports from Prompt 1. The top and bottom third trials were identified based on RRT variance and organized into the following four conditions: on-task + high variance (on-high), on-task + low variance (on-low), off-task + high variance (off-high), and off-task + low variance (off-low) (summarized in Figure 1). A linear mixed effects analysis was run to compare RRT variance across performance variability (high vs low) and attention state (on-task vs off-task).

As expected, and by design, a significant main effect of performance was observed, indicating that RRT variance in the high variability condition was significantly greater than in the low variability condition, $F(1, 80) = 807.91$, $p < .0001$. In addition, there was a significant main effect of attention state, $F(1, 80) = 21.114$, $p < .0001$, where off-task thoughts had greater mean RRT variance than on-task thoughts. The interaction between attention state and performance was not significant, $F(1, 80) = .201$, $p = .655$.

To understand further the relationship between each attention state and performance level, post-hoc tests were conducted for all paired comparisons. This resulted in six paired comparison tests and Tukey correction was applied. All comparisons were significant, all *z*s > |3|, all *p*s < .013. Results are illustrated in Figure 13.

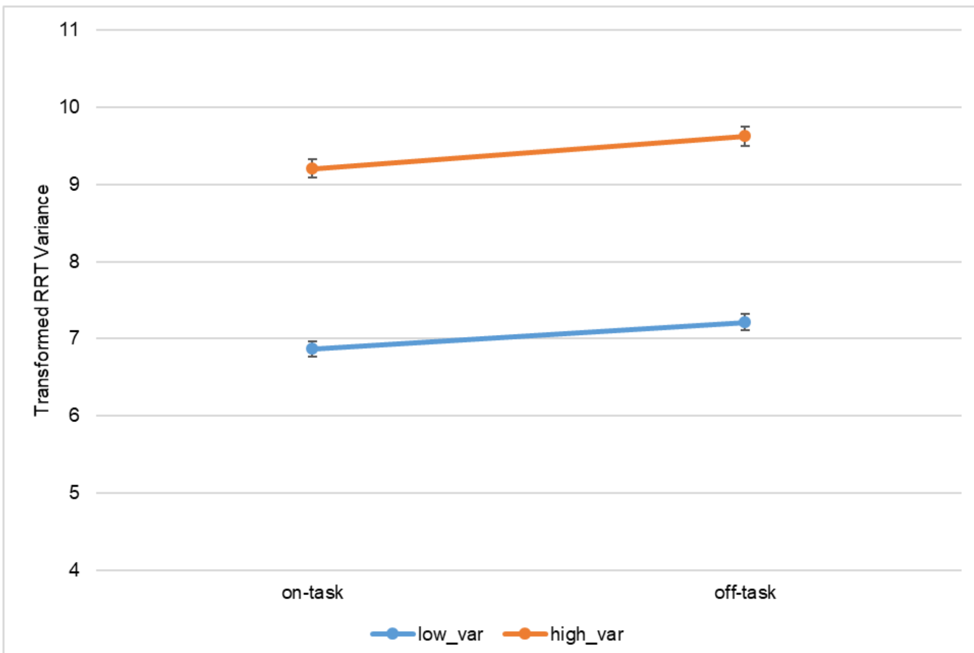

Figure 13 – Quadrant State Analysis. Mean RRT variance calculated from the top and bottom third of on-task and off-task attention states.

Overall, there were large significant differences between trials with the highest variance compared to the lowest variance, along with differences between on-task and off-task trials. As hypothesized, the most extreme low-variance trials were reported on average as on-task, and the most extreme high-variance trials were reported on average as off-task. Interestingly, however, off-low trials were significantly more variable than on-low trials, even though both were characterized by low variance. Furthermore, off-high trials were significantly more variable than on-high trials, even though both were characterized by high variance. Together, these contrasts suggest that over and above objective behavioral performance, an individual's subjective attention state can provide additional information regarding attention and performance. These findings are further addressed in the Discussion.

2.2.3 Pupillometry

Prompt 1. There was no main effect of attention state, $F(3, 60) = .16$, $p = .923$. Because each epoch was baseline-corrected by dividing the time series by the median pupil diameter of the baseline, an epoch with a mean value of 1 would indicate no change from baseline. When tested against the baseline = 1, mean pupil diameters were significantly smaller than baseline for task-related thoughts $t(23) = -3.704$, $p = .001$ and off-task thoughts, $t(22) = -4.840$, $p < .001$. However, mean pupil diameter was not significantly different from baseline for on-task thoughts, $t(21) = -1.787$, $p = .088$ or the inattentive state, $t(17) = -.912$, $p = .374$. Results are illustrated in Figure 14.

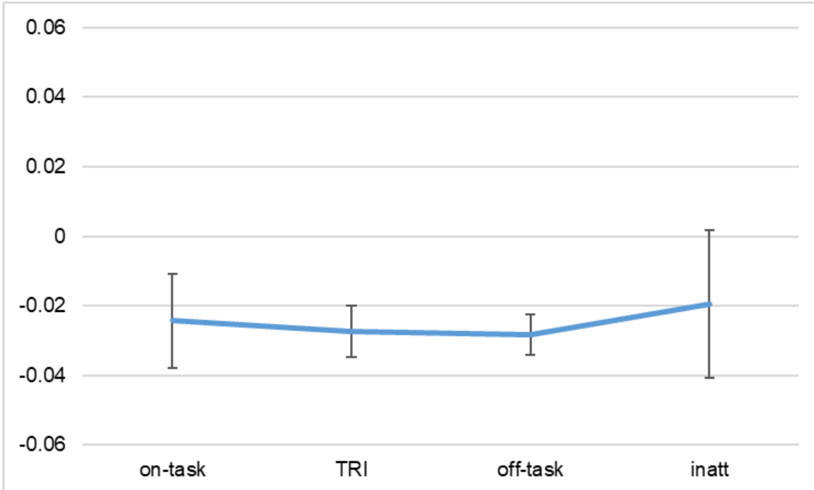

Figure 14 – Pupil diameter relative to baseline for Prompt 1. For visualization, baseline here is at y = 0.

Prompt 2 and 3. To examine the effect that environment and dynamics had on pupil diameter, a 2x2 linear mixed effects model was run. This model indicated a significant main effect of dynamics, $F(1, 41) = 7.278$, $p = .010$, with smaller pupil diameter on average corresponding with spontaneous thoughts. Results also indicated a significant interaction between environment and dynamics, $F(1, 41) = 4.175$, $p = .048$. As shown in Figure 15, this interaction was driven by the internal attention state where internally directed spontaneous thoughts had smaller pupil diameters compared to internally directed constrained thoughts. There was no significant effect of environment, $F(1, 41) = 1.821$, $p = .185$.

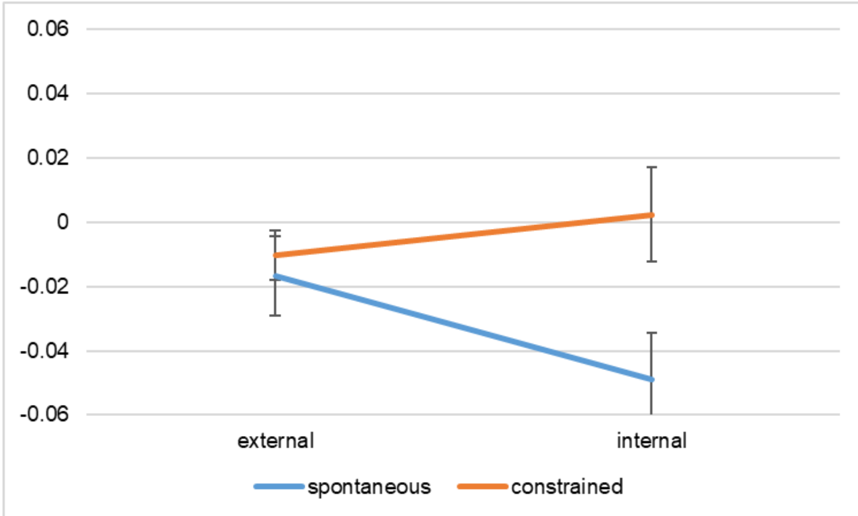

Figure 15 – Pupil diameter relative to baseline for Prompts 2 and 3. For visualization, baseline here is at y = 0. There was a significant main effect of dynamics and a significant interaction, where pupil diameter for internal-spontaneous thoughts was smaller than internal-constrained thoughts.

Prompt 2. To test for differences between baseline and mean pupil diameter in each environmental state, one-sample t-tests were run against the null hypothesis *baseline = 1*. Bonferroni correction was applied for multiple comparison correction. Pupil diameter was significantly smaller for the internal attention state, $t(22) = -3.842$, $p < .001$. Pupil diameter was also smaller for the external attention state, however this result did not reach significance, $t(20) = -1.947$, $p = .066$.

Prompt 3. A separate set of one-sample t-tests were run to test for differences between baseline and mean pupil diameter in each dynamic state. Bonferroni correction was applied. Pupil diameter was significantly smaller for the spontaneous attention state when compared to baseline = 1, $t(22) = -5.782$, $p < .001$. There was no difference between pupil diameter for the constrained attention state and baseline, $t(19) = -.341$, $p = .737$.

2.2.4 fMRI Analysis

Prompt 1: Whole Brain Analysis. A whole brain analysis was run in AFNI using a linear mixed effects model to examine BOLD response across the different attention states of Prompt 1. The first general linear test examined brain activity during the on-task state compared to all forms of distraction (task-related interference, off-task, and inattentive states). In general, significant activation in BOLD signal was observed during distraction states across the orbital frontal gyrus near the medial PFC and in the left inferior frontal gyrus. In addition, activation was observed in the right lingual gyrus, the left postcentral gyrus, and supplementary motor area during distraction states. No activation associated with on-task thoughts survived whole-brain correction. Significant clusters of activation associated with the distraction states are listed in Table 4.

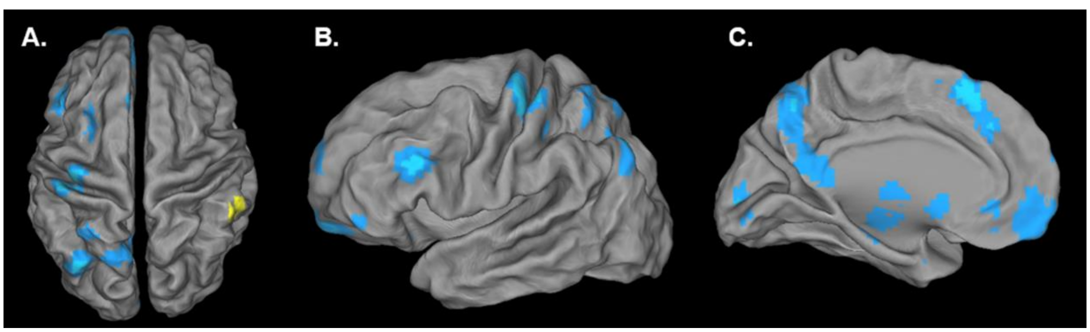

Figure 16 – Prompt 1. Contrast of on-task > off-task (FDR-corrected q = .05)
A) Axial view. B) Left hemisphere, lateral sagittal view. C) Left hemisphere, medial sagittal view.

A series of additional general linear tests were run to compare each pair of attention states. When contrasting off-task thoughts with on-task thoughts (Figure 16), there was significant activation in many DMN regions along with the left precentral and postcentral gyrus. Significant activation for on-task thoughts was observed in the right inferior parietal lobule. When contrasting off-task thoughts to the inattentive state, there was activation observed in regions including the left middle frontal gyrus, left precuneus, left inferior parietal lobule, bilateral caudate nucleus, and bilateral cuneus (Figure 17). Activation was observed in the right inferior frontal gyrus for the inattentive state. Significant clusters of activation are listed in Table 4. There was no significant activity when contrasting on-task and TRI attention states.

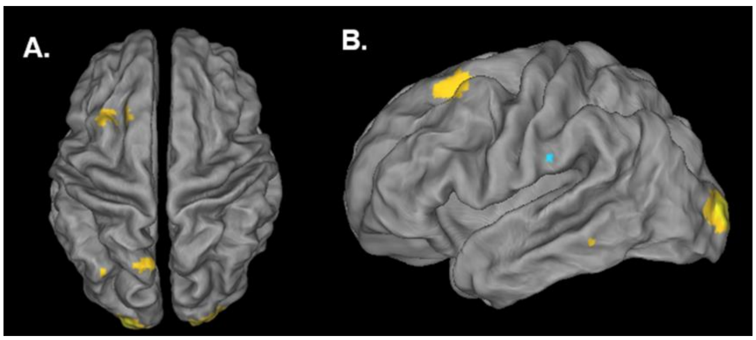

Figure 17 – Prompt 1. Contrast of off-task > inattentive (FDR-corrected q = .05) A) Axial view. B) Left hemisphere, lateral sagittal view.

Two conjunction analyses were performed to examine further the patterns of neural activity pertaining to individual distraction states. The first analysis tested which voxels were significant in both the off-task and inattentive states compared to the on-task state (off-task > on-task ∩ inattention > on-task). Shared activity in both states was observed in the left inferior frontal gyrus and left ACC. Activity in the off-task state, which was not present in the inattentive state, was observed in a large set of DMN and MTL regions, including the precuneus, parahippocampal gyrus, and inferior frontal gyrus. Activation in the insula was also observed. Activity in the inattentive state, which was not present in the off-task state, was observed in subregions of both the ventral and dorsal ACC and left inferior frontal gyrus. To further isolate off-task activity, a second conjunction analysis was performed on the off-task state compared to both the inattentive and on-task conditions (off-task > on-task ∩ off-task > inattention). Activation associated with the off-task state in both contrasts was observed in the left middle frontal gyrus, left precuneus, right lingual gyrus, left superior medial gyrus, and right cerebellum.

In general, as predicted and replicating much previous research, increased DMN activation was observed during off-task thoughts and distraction states in general. Increased activity during the distraction states, in particular the off-task and inattention states, was also observed in left motor areas, perhaps associated with increased behavior variability when attention oriented away from the task. In addition, activation in frontoparietal "task-positive" regions was observed in the off-task state compared to inattention, in line with the role these regions have in off-task thought such as planning and problem solving.

Table 4 - Regions with significant activation (FDR correction *q* = .05) for each contrast of the Prompt 1 whole brain analysis. The number of voxels pertains to the size of each cluster identified in AFNI. The peak of each cluster is indicated with MNI coordinates. The region is the anatomical region of the cluster peak identified with the CA_ML_18_MNIA atlas in AFNI.

Contrast	Number of Voxels	x	y	z	Hemisphere	Region	Condition
on-task vs. all distraction states							
	220	-45	-24	63	left	postcentral gyrus	all distraction states
	23	-42	24	21	left	inferior frontal gyrus	all distraction states
	11	6	-87	-3	right	lingual gyrus	all distraction states
	9	-12	51	-12	left	middle orbital gyrus	all distraction states
	8	-18	-60	27	left	cuneus	all distraction states
	6	-6	21	54	left	SMA	all distraction states
on-task vs. TRI							
	n/a	n/a	n/a	n/a		n/a	n/a
on-task vs. off-task							
	653	-33	-72	45	left	inferior parietal lobule	off-task
	450	-45	-24	69	left	postcentral gyrus	off-task
	299	-9	51	-12	left	mid orbital gyrus	off-task
	193	-48	24	24	left	inferior frontal gyrus	off-task
	142	-21	-24	-9	left	hippocampus	off-task
	131	60	-30	54	right	inferior parietal lobule	on-task
	127	-6	18	51	left	SMA	off-task
	125	21	-87	-33	right	cerebellum	off-task
	101	3	-87	0	right	calcarine gyrus	off-task
	63	-30	-54	60	left	superior parietal lobule	off-task
	59	-9	3	-3	left	pallidum	off-task
	33	-18	63	15	left	superior frontal gyrus	off-task
	30	-24	36	-15	left	middle orbital gyrus	off-task
	27	21	-33	-39	right	cerebellum	off-task
	19	-45	45	-3	left	inferior frontal gyrus	off-task
	17	21	-51	-18	right	cerebellum	off-task
	14	12	15	3	right	caudate nucleus	off-task
	14	-51	18	48	left	middle frontal gyrus	off-task
	13	-24	21	-9	left	insula	off-task
	10	-36	33	0	left	inferior frontal gyurs	off-task
	6	45	-69	-45	right	cerebellum	off-task

6	39	-72	-36	right	cerebellum	off-task
6	-45	-90	6	left	middle occipital	on-task
5	54	-57	-27	right	cerebellum	off-task

Quadrant State Analysis. To examine brain activity across high and low performance variability and on-task and off-task attention states, a separate whole brain analysis was run with a linear mixed effects model. A set of six contrasts were run to compare brain activity across each combination of attention state and performance, as in the behavioral analysis: on-high, on-low, off-high, and off-low.

No significant activity survived whole-brain correction in the following general linear contrasts: on-low versus on-high; off-low versus off-high, and on-low versus off-low. In addition, there was no significant activity in the contrast on-high versus off-low.

Whereas most whole-brain contrasts did not yield significant results, when comparing the off-high condition to the on-high condition, there was extensive activity in the off-high condition throughout the brain (Figure 18), perhaps due to the more extreme nature of being in an off-task, high performance variability state compared to on-task, regardless of the performance variability in the on-task state. Similar to the results of Prompt 1 described above, this activity was observed in areas belonging to the DMN, including the precuneus, medial prefrontal cortex, inferior frontal gyrus, inferior parietal lobule, and angular gyrus. In addition, activation was observed over the bilateral motor cortex as well as regions including the insula, superior parietal lobule, and occipital regions. When comparing activation in off-high to on-low, a similar but less extensive pattern of significant activity was observed. Activation during the off-high condition was observed in the precuneus and inferior parietal lobule, as well as the middle and superior frontal gyrus, superior parietal lobule, and motor cortex.

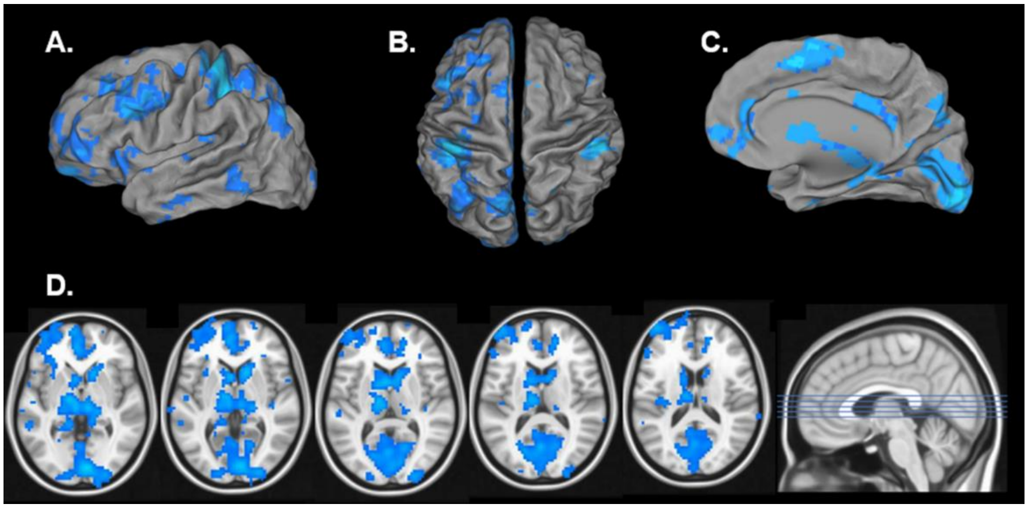

Figure 18 – Quadrant State Analysis. Contrast of on-high > off-high (FDR-corrected *q* = .05) A) Left hemisphere, lateral sagittal view. B) Axial view. C) Right hemisphere, medial sagittal view. D) Multislice axial view of on-high > off-high contrast.

In the DMN percent signal change analysis, there was a significant main effect of attention state, $F(1, 80) = 4.42$, $p = .039$. There was a trending but nonsignificant interaction between attention state and performance variance, $F(1, 80) = 2.83$, $p = .096$. There was no main effect of performance variance, $F(1,80) = .040$, $p = .843$. Overall, there was decreased signal in the DMN during the on-task attention state compared to off-task, and the greatest difference in activation was observed between the off-high condition and the on-high condition. Results are summarized in Figure 19.

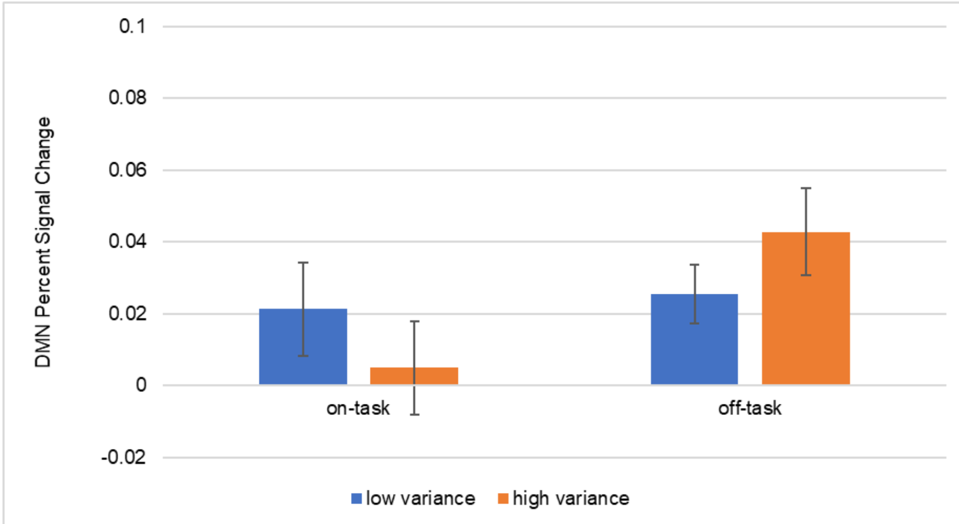

Figure 19 – Quadrant State Analysis. DMN percent signal change as a function of attention state and performance variance. There was a main effect of attention state and a trending but nonsignificant interaction between attention state and performance.

Prompt 2: Whole Brain Analysis. This contrast examined the effect of environmental orientation of attention state on brain activity. There was no significant activity associated with internally orientated attention states. Significant activity associated with externally oriented attention included right inferior parietal lobule and right insula, consistent with externally oriented attention and saliency processing. Significant activity in externally oriented attention was also observed in right Heschl's gyrus, consistent with auditory processing.

Prompt 3: Whole Brain Analysis. The contrast for Prompt 3 focused specifically on the dynamics of internally-directed thoughts. There were too few trials categorized as externally oriented to run a factorial analysis examining environment by dynamics. In addition, it was theoretically interesting to constrain the Prompt 3 analysis to internally-directed thoughts, as this would provide insight to the dynamics of classically defined “task-unrelated and stimulus independent” mind wandering instances (Christoff, 2012; Christoff et al., 2016). No significant activity was observed for spontaneous thoughts. However, for constrained thoughts, a significant cluster of activity was observed in the left hippocampal region (Figure 20).

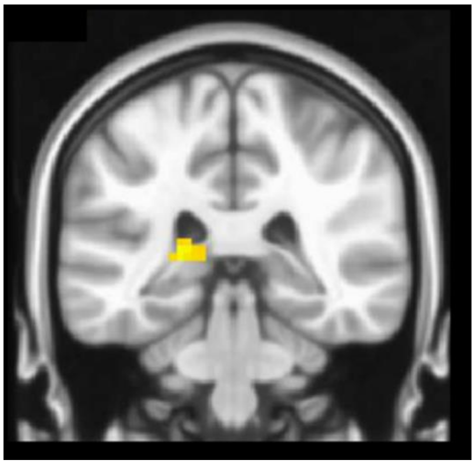

Figure 20 – Prompt 3. Internal-constrained > Internal-spontaneous contrast (FDR corrected *q* = .05)

Functional Connectivity Analysis. To examine further the neural correlates of the dynamics of thought, beta series functional connectivity analyses were run on Prompt 3, again focusing on internally-directed thought dynamics. Functional connectivity analysis within the DMN, with the left hippocampus serving as the seed region, showed no significant differences between constrained and spontaneous thoughts, all ps > .10 (Table 5). When testing each set of correlations against the null hypothesis $r = 0$, there was significant connectivity between the left hippocampus and right hippocampus for spontaneous thoughts (M = .458, SEM = .13), $t(14) = 3.59$, p = .003 (Bonferroni corrected; Table 6).

Functional connectivity analysis within the FPCN, with the left dlPFC serving as the seed region, showed no significant differences between internal-constrained and internal-spontaneous in any FPCN node pairs (Table 5). When testing each set of correlations against the null hypothesis $r = 0$, several significant correlations for spontaneous and constrained thoughts were observed following Bonferroni correction. These results are summarized in Table 6.

Table 5 - Functional connectivity between internal spontaneous and constrained thoughts for both the DMN (seed: left hippocampus) and the FPCN (seed: left dlPFC). Correlation values are fisher-transformed. No comparisons were significant. Abbreviations: prefrontal cortex (PFC); posterior cingulate cortex (PCC); anterior medial PFC (amPFC); dorsomedial PFC (dmPFC); angular gyrus (Ang); inferior frontal gyrus (IFG); superior frontal gyrus (SFG); superior temporal sulcus (STS); temporoparietal junction (TPJ); hippocampal formation (HF); anterior temporal lobe (aTemp); ventromedial PFC (vmPFC); medial frontal gyrus (MFG) anterior inferior parietal lobule (aIPL); anterior insula (aIns); rostrolateral PFC (rlPFC); medial superior PFC (msPFC); dorsal anterior cingulate cortex (dACC)

	Seed	ROI	Mean internal-spontaneous *r (SEM)*	Mean internal-constrained *r (SEM)*	t	*p*-value
DMN	left hipp	PCC	.129 *(.10)*	.452 *(.19)*	-1.546	.144
		amPFC	.135 *(.10)*	.355 *(.19)*	-0.879	.394
		dmPFC	.081 *(.11)*	.244 *(.21)*	-0.604	.555
		left Ang	.278 *(.10)*	.427 *(.15)*	-0.708	.490
		left IFG	.149 *(.11)*	.232 *(.18)*	-0.341	.738
		left SFG	.037 *(.12)*	.342 *(.17)*	-1.719	.108
		left STS	.056 *(.15)*	.184 *(.15)*	-0.544	.595
		left TPJ	.048 *(.12)*	.238 *(.15)*	-0.865	.402
		left aTemp	.215 *(.15)*	.177 *(.20)*	0.146	.886
		right Ang	.083 *(.13)*	.513 *(.29)*	-1.309	.212
		right HF	.458 *(.13)*	.629 *(.30)*	-0.518	.613
		right IFG	-.008 *(.12)*	.235 *(.13)*	-1.266	.226
		right STS	.195 *(.08)*	.409 *(.17)*	-1.009	.330
		right TPJ	.206 *(.07)*	.025 *(.19)*	0.840	.415
		right aTemp	.093 *(.09)*	.177 *(.20)*	-0.350	.731
		vmPFC	.266 *(.09)*	.265 *(.20)*	0.007	.994
FPCN	left dlPFC	left MFG (BA6)	.355 *(.11)*	.813 *(.23)*	-1.932	.074
		left MFG (BA9)	.803 *(.09)*	.937 *(.27)*	-0.550	.591
		left aIPL	.704 *(.12)*	.550 *(.22)*	0.647	.528
		left aIns	.321 *(.13)*	.094 *(.20)*	0.915	.376
		left rlPFC	.436 *(.13)*	.618 *(.28)*	-0.617	.547
		msPFC	.631 *(.14)*	.821 *(.18)*	-0.861	.404
		right MFGBA6	.320 *(.09)*	.579 *(.26)*	-0.889	.389
		right MFGBA9	.544 *(.13)*	.511 *(.20)*	0.124	.903
		right SFG	.314 *(.10)*	.309 *(.22)*	0.022	.983
		right aIPL	.469 *(.15)*	.423 *(.21)*	0.144	.888

right aIns	.224 *(.12)*	.448 *(.19)*	-0.858	.405
right dACC	.537 *(.15)*	.835 *(.23)*	-1.093	.292
right dlPFC	.601 *(.16)*	.657 *(.19)*	-0.174	.864
right rlPFC	.473 *(.14)*	.792 *(.25)*	-0.929	.369

Table 6 - Summary of functional connectivity of each ROI tested against the null hypothesis *r* = 0. *: Significant after Bonferroni correction (family-wise correction within each network and attention state). During spontaneous thoughts, the right HF was significantly correlated with the DMN seed (left hippocampus). Within the FPCN, there was significant functional connectivity between several ROIs and the seed (left dlPFC) during spontaneous and constrained internal attention states.

			internal-spontaneous			internal-constrained		
	Seed	**ROI**	**Mean *r* *(SEM)***	**t**	***p*-value**	**Mean *r* *(SEM)***	**t**	***p*-value**
DMN	**left hipp**	PCC	.129 *(.10)*	1.341	.201	.452 *(.19)*	2.364	.033
		amPFC	.135 *(.10)*	1.390	.186	.355 *(.19)*	1.841	.087
		dmPFC	.081 *(.11)*	0.763	.458	.244 *(.21)*	1.147	.271
		left Ang	.278 *(.10)*	2.779	.015	.427 *(.15)*	2.925	.011
		left IFG	.149 *(.11)*	1.395	.185	.232 *(.18)*	1.271	.224
		left SFG	.037 *(.12)*	0.317	.756	.342 *(.17)*	1.955	.071
		left STS	.056 *(.15)*	0.379	.711	.184 *(.15)*	1.242	.235
		left TPJ	.048 *(.12)*	0.403	.693	.238 *(.15)*	1.595	.133
		left aTemp	.215 *(.15)*	1.393	.185	.177 *(.20)*	0.866	.401
		right Ang	.083 *(.13)*	0.630	.539	.513 *(.29)*	1.793	.095
		right HF	.458 *(.13)*	3.595	.003 *	.629 *(.30)*	2.074	.057
		right IFG	-.008 *(.12)*	-.063	.950	.235 *(.13)*	1.744	.103
		right STS	.195 *(.08)*	2.349	.034	.409 *(.17)*	2.428	.029
		right TPJ	.206 *(.07)*	2.998	.010	.025 *(.19)*	0.131	.897
		right aTemp	.093 *(.09)*	1.000	.334	.177 *(.20)*	0.872	.398
		vmPFC	.266 *(.09)*	3.075	.008	.265 *(.20)*	1.330	.205
FPCN	**left dlPFC**	left MFG (BA6)	.355 *(.11)*	3.353	.005	.813 *(.23)*	3.489	.004
		left MFG (BA9)	.803 *(.09)*	9.375	< .001 *	.937 *(.27)*	3.532	.003 *
		left aIPL	.704 *(.12)*	5.646	< .001 *	.550 *(.22)*	2.447	.028
		left aIns	.321 *(.13)*	2.454	.028	.094 *(.20)*	0.463	.650
		left rPFC	.436 *(.13)*	3.468	.004	.618 *(.28)*	2.210	.044
		msPFC	.631 *(.14)*	4.441	.001 *	.821 *(.18)*	4.447	.001 *
		right MFGBA6	.320 *(.09)*	3.480	.004	.579 *(.26)*	2.232	.043
		right MFGBA9	.544 *(.13)*	4.355	.001 *	.511 *(.20)*	2.517	.025
		right SFG	.314 *(.10)*	3.211	.006	.309 *(.22)*	1.373	.192
		right aIPL	.469 *(.15)*	3.026	.009	.423 *(.21)*	2.050	.060
		right aIns	.224 *(.12)*	1.897	.079	.448 *(.19)*	2.371	.033
		right dACC	.537 *(.15)*	3.655	.003 *	.835 *(.23)*	3.683	.002 *
		right dlPFC	.601 *(.16)*	3.849	.002 *	.657 *(.19)*	3.379	.004
		right rPFC	.473 *(.14)*	3.428	.004	.792 *(.25)*	3.166	.007

To examine more broadly the roles of the DMN and FPCN in thought dynamics, network functional connectivity was examined. There was a trending but nonsignificant difference in DMN connectivity between constrained (*M* = .624, *SEM* = .136) and spontaneous thoughts (*M* = .336, *SEM* = .025), *t*(14) = 2.123, *p* = .052. However, there was no significant difference in FPCN connectivity between constrained (*M* = .620, *SEM* = .142) and spontaneous thoughts (*M* = .457, *SEM* = .053), *t*(14) = 1.066, *p* = .304. When examining connectivity between the DMN and FPCN, there was increased between-network connectivity during constrained thoughts (*M* = .514, *SEM* = .143) compared to spontaneous thoughts (*M* = .262, *SEM* = .035). However, this difference did not reach significance, *t*(14) = 1.766, *p* = .099.

There was no significant difference in within-network connectivity in the DMN (*M* = .624, *SEM* = .136) and within-network connectivity in the FPCN (*M* = .620, *SEM* = .142) during internal-constrained thoughts, *t*(14) = .033, *p* = .974. However, there was a significant difference between connectivity in the DMN (*M* = .336, *SEM* = .025) and the FPCN (*M* = .457, *SEM* = .053) during internal-spontaneous thoughts, *t*(14) = -3.304, *p* = .005.

2.3 Summary and Discussion

The MRT procedure coupled with an extensive set of thought probes provided a way to examine the relationship between attention states and performance variability. In addition, incorporating fMRI and pupillometry measures provided a way to investigate further the mechanisms of off-task thought and other attention states. Importantly, the results replicated previous research that had found increased RRT variability during off-task compared to on-task thought (Seli et al., 2013). More interesting, however, was the pattern of RRT variability across the attention state categories of Prompt 1. RRT variability increased linearly from the on-task attention state to the inattentive attention state (Figure 9). Although the attention states were defined categorically, one possible interpretation of these findings is that the RRT variability pattern reflects a process of disengagement across the attention states. Understanding mind wandering and attention lapses from a perspective of disengagement has been proposed previously. For example, Cheyne and colleagues (2009) described mind wandering in terms of disengagement over the course of distinct states, where an individual can range from being in a state of transient disengagement to full "decoupling" from the task, where errors are most extreme. To investigate more in depth the relationship between behavioral performance and attention states, an ex-Gaussian analysis was conducted on the raw RRT variability values. It should be noted that the results of the ex-Gaussian analysis should be interpreted conservatively as pilot data, given the limited number of trials used compared to the typical requirements of ex-Gaussian analyses (Heathcote et al., 1991). The ex-Gaussian analysis yielded a significant main effect of attention state for the *tau* parameter, where the off-task and inattentive states were significantly greater than the on-task attention state. In general, these results indicate that the distributions of RRT variability for the more distracted states (i.e., off-task and inattentive) are significantly more skewed and reflect the fact that not only is performance variability increased on average, but that the variance of RRT variability is greater. These results suggest that during these more distracted states, the underlying mechanisms may be characterized by increased volatility and unpredictability. These results are discussed further in the Discussion.

A quadrant state analysis was conducted to examine both the behavioral and neural characteristics of on-task and off-task thoughts across periods of low and high performance variability. By design, there was a significant main effect of performance variability. In addition, there was a significant main effect of attention state and all pairwise comparisons were significant (Figure 13). In particular, within low performance variability, there was a small but significant difference between on-task and off-task. Similarly, within high performance variability, there was a small but significant difference between on-task and off-task. These results indicate that while these differences are small, self-reported attention states provide additional, important information beyond that provided by performance variability. The implications of these behavioral results are addressed further in the Discussion. Despite the behavioral dissociation, there were fewer significant results in the fMRI quadrant state analysis. Overall, a large amount of significant activity was observed in the contrast of off-high compared to on-high. This activity was observed across the DMN as well as the bilateral motor cortex, insula, superior parietal lobule, and occipital regions. A similar, yet attenuated, pattern of significant activity was observed in the contrast of off-high compared to on-low. These results reflect the involvement of a number of brain regions that have been associated previously with off-task thought (Fox et al., 2015). The lack of a pattern of neural findings similar to that of the behavioral dissociation may be due to the underpowered nature of the design. The top and bottom third of trials were used from each attention state per participant. This may have resulted in too few trials in the fMRI analysis to detect at the whole brain level the subtle differences across task conditions that were observed with RRT variability. To focus specifically on the DMN, an ROI-based percent signal change analysis was conducted by extracting the average beta weights (coefficients) from the DMN. The overall results indicated a main effect of increased DMN activity during the off-task compared to the on-task attention state, thus further replicating numerous previous studies. However, while the interaction did not reach significance, the overall pattern of results (shown in Figure 19) suggests there is an indication that a moderate amount of DMN activity is associated with low variability performance, regardless of the subjective attention state, a finding that is in line with those of Esterman et al. (2012).

In addition, the neural correlates were investigated for each of the attention states of the three prompts. Overall, the fMRI results of Prompt 1 indicated increased DMN activity during the off-task compared to the on-task state, again replicating many previous findings. Furthermore, conjunction analyses revealed activity in frontoparietal regions unique to the off-task state, supporting the research that suggests these regions are recruited to drive off-task thought processing along with the DMN. In addition, a large amount of activity was observed in the left motor regions, likely reflecting the increased performance variability associated with these conditions.

Separate whole brain analyses were conducted for Prompts 2 and 3. In Prompt 2, an increase in fMRI activity was observed for external compared to internal attention states within the right inferior parietal lobule and right insula, consistent with externally oriented attention and saliency processing. Significant activity in externally oriented attention was also observed in right Heschl's gyrus, consistent with auditory processing. For Prompt 3, analyses concentrated on just the internal constrained and spontaneous attention states, due to the limited number of external attention states. In addition, focusing analyses on just the internal constrained and spontaneous states was theoretically meaningful and allowed for analyzing what have often been referred to as “stimulus-independent, task-unrelated thoughts” (Stawarczyk et al., 2011). Here, both whole brain and functional connectivity analyses were conducted. The whole brain analysis revealed a small amount of significant activation for constrained compared to spontaneous thoughts within the left hippocampal region. Most interesting, however, were the functional connectivity results. Functional connectivity calculated between all pairs of ROIs comprising the DMN and FPCN indicated overall increased functional connectivity during constrained compared to spontaneous attention states. In addition, there was a significant decrease in connectivity within the DMN for spontaneous compared to constrained thoughts. This decrease within the DMN for spontaneous thoughts may support the inherent variability and unconstrained nature that characterizes this attention state. The implications of these results and their potential mechanisms are discussed further in the Discussion.

Last, in regard to pupillometry, there were no differences in pupil diameter across the attention states of Prompt 1. This was rather surprising given the previous findings that have documented differences in pupil diameter between on-task and off-task thought (e.g., Franklin et al., 2013). This lack of difference may be due to technical aspects of the experimental setting. For example, pupil diameter fluctuates due to changes in lighting (Sirois & Brisson, 2014). Although participants were instructed to remain focused on the fixation cross in the middle of the screen, they were likely engaged in a variety of looking patterns across the screen and towards other parts of the MRI scanner. This could result in a large number of changes in pupil diameter that are irrelevant to attention states (Sirois & Brisson, 2014). In addition, from a theoretical perspective, it is possible that differences failed to emerge due to motivation and arousal. Changes in pupil diameter reflect fluctuations in arousal levels (Lenartowicz et al., 2013). Often, these fluctuations in arousal levels correspond to the current attention state of an individual (Lenartowicz et al., 2013). However, if arousal does not change across attention states, despite the subjective differences between each attention state, then pupil diameter will not effectively index distraction. While there were no differences in pupil diameter across the attention states of Prompt 1 (and thus, possibly no changes in arousal levels), when breaking down off-task thought into its environmental orientation and dynamics, there were significant differences in pupil diameter. There was a significant interaction between Prompt 2 and Prompt 3, where pupil diameter for internal, spontaneous thoughts was decreased compared to internal, constrained thoughts. More specifically, average pupil diameter for internal, constrained thoughts was comparable to baseline, and average pupil diameter for internal, spontaneous thoughts was decreased relative to baseline. It is possible that focused, constrained thoughts, and the corresponding arousal level, are similar to the attention state one is in during the baseline period, where the individual is re-focused on the task and preparing to begin a new tapping period. However, spontaneous thoughts may reflect not just a decoupling from a directed, focused attention state but also changes in arousal level as one lapses into freely moving off-task thought. It is possible that these differences in arousal can then be indexed with pupil diameter, as suggested with the current data. While pupil diameter on average did not change across the broad attention state of Prompt 1, when taking a more nuanced approach to off-task thought via Prompt 2 and Prompt 3, subtle but significant differences in pupil diameter (and likely corresponding arousal levels), begin to emerge.

CHAPTER 3. STUDY 2

3.1 Method

3.1.1 Participants

A total of 33 participants were recruited from the Georgia Institute of Technology. The age of participants ranged from 18 to 25 (*M* = 20, *SD* = 1.8). All participants were right-handed, had normal or corrected-to-normal vision and hearing, and reported no neurological or psychiatric disorders. The data from one participant was excluded due to technical issues, leaving data from a total of 32 participants for analysis.

3.1.2 Metronome Response Task (Two-Tone Version)

This version of the MRT consisted of two conditions in which cognitive demand was manipulated across blocks: the easy condition (low cognitive demand), which consisted of the one-tone task, and the difficult condition (high cognitive demand), which consisted of the two-tone task. The easy condition was identical to the task in Study 1, in which participants tapped synchronously to a 450-Hz metronome tone using their right index finger. The difficult task consisted of a low-pitch tone (550 Hz) and a high-pitch tone (750 Hz). Participants were taught two tapping patterns that corresponded to these two tones. Both tapping patterns consisted of sequences using all four fingers of the right hand. The low-pitch tapping pattern followed the order of 'ring-index-middle-little', where participants tapped their fingers in the order of ring finger, index finger, middle finger, little finger. The high-pitch tapping pattern followed the order of 'little-middle-ring-index', where participants tapped their fingers in the order of little finger, middle finger, ring finger, index finger. During the tapping periods, the two tones alternated back and forth at variable frequencies, and a change in pitch indicated to participants which tapping sequence to perform. The tapping sequence was always performed synchronously with the metronome, regardless of the pitch. For example, during a particular tapping period consisting of 24 metronome beeps, the first nine beeps may be at the 550-Hz pitch, the next seven beeps may be at the 750-Hz pitch, and the final eight beeps may be at the 550-Hz pitch. In this case, participants would use the low-pitch sequence to tap along to the first nine beeps. Upon hearing the tone change, participants would switch to the high-pitch sequence for those seven beeps, and then switch back to the low-pitch sequence for the final eight beeps. For both task conditions and all tapping patterns, the metronome always sounded for 75 ms at a rate of 1300 ms per tone.

3.1.3 Thought Probes

The thought probes were identical to those in Study 1. Participants were presented with a thought prompt at the end of each tap period that asked them to classify the thought they had just prior to the onset of the probe. The thought prompt was presented for 6 s. If participants selected the "off-task" option, they then responded to the two additional thought probes, presented for 5 s each. Otherwise, a fixation remained on the screen for 10 s until the next tapping period began. As in Study 1, participants were given detailed explanations of the thought prompts before beginning the experiment (Appendix A).

3.1.4 Experimental Procedure

The MRT was run using E-Prime software. All visual stimuli were presented in white font on a black background. At the start of the study, a sound and pitch test was performed for each participant to ensure that the sound was at a suitable volume and to confirm whether participants were able to detect the differences between the two pitches used in the high cognitive load condition. Participants listened to the two pitches and verbally confirmed whether they detected a difference. All participants reported clearly detecting the two tones.

The experiment consisted of eight blocks of tapping periods. There were four blocks of the easy condition and four blocks of the difficult condition, presented pseudo-randomly such that the first four blocks and the second four blocks each consisted of two easy conditions and two difficult conditions. Participants were instructed to keep their eyes open and focus on a fixation in the center of the screen. At the start of each block, participants were informed whether they would perform the one-tone task or the two-tone task. Then a baseline fixation was presented in the center of the screen for a variable duration of 2 – 4 s. The metronome began after the baseline. Participants were instructed to begin tapping at the start of the metronome and to tap as synchronously as possible using the appropriate tapping sequence(s) for the duration of the tapping period. All blocks consisted of 15 tapping periods with variable durations between 16 and 36 s. These durations followed the same distribution as in Study 1. In the difficult condition, the tapping sequence switched pseudo-randomly. Because analyses focused on performance of the five taps preceding the thought prompts, the tapping sequences never switched during the last five beeps of a tapping period. This allowed for analysis of attention state and performance variability without any confounds associated with the act of switching between tap sequences. After the completion of each tapping period, participants were presented with the same sequence of thought probes as in Study 1. Following the experiment, participants completed a questionnaire regarding their experience during the study.

A training and practice session were performed at the start of the study to familiarize participants with the task and the tapping sequences. The training session consisted of practicing the three tapping sequences until they could perform them with minimal errors. After the training session, participants performed a practice experiment session where they practiced two short blocks of each task condition and responded to the thought prompts.

3.1.5 Statistical Analysis

Before statistical analysis, performance accuracy was calculated for each tapping period. In all conditions, all missing and incorrect taps were counted as errors. For the difficult condition, it was possible that participants made mistakes in the tapping sequences throughout the duration of the tapping period. Therefore, accuracy was determined based on comparing the performed 5-tap sequence preceding the prompt with the assigned tapping pattern, starting with the first of the last five taps. In the event that the first tap was missing, the sequences were compared starting with the second performed tap. To be included in analysis, each trial needed to have at least three correctly performed taps out of the five total. With these exclusion criteria, an average of 6% (*SEM* = 1.21%) of trials were removed from each participant's data. This included an average of 3% (*SEM* = .80%) of trials from the easy condition and 10% (*SEM* = 1.90%) of trials from the difficult condition.

As in Study 1, the RRT variance was calculated from the last five taps of each tapping period and was then transformed using the natural log transform. For statistical analysis of RRT variance as a function of condition and attention state, linear mixed-effects models were run using the *lme* function from the *nlme* package in R. In all statistical analyses of RRT variance, only cells consisting of two or more reports were included in analysis.

The frequency of each attention state in Prompt 1 was calculated within task level as a proportion out of all valid trials in each task level. Because Prompts 2 and 3 are nested within the off-task response of Prompt 1, the frequency of each attention state from these prompts was calculated as a proportion out of all valid off-task trials in each task level. The arcsine transformation (defined as $sin^{-1}\sqrt{p}$ where p is the proportion) was applied to all proportion values before running inferential statistics. For interpretability, all descriptive statistics and figures depict the raw values.

3.2 Results

3.2.1 Self-Report Measures

Prompt 1. The proportions of each attention state response were calculated within task level and are shown in Figure 21. To test for significant differences, a 2x2 linear mixed-effects model was run with Prompt 1 and task level as factors. There was a main effect of Prompt 1, $F(3, 217) = 11.828$, $p < .001$ and a significant interaction between Prompt 1 and task level, $F(3, 217) = 6.512$, $p = .0003$. The main effect of task level was not significant, $F(3, 217) = .354$, $p = .553$. A series of paired comparisons was run to test for significant differences in proportions within each task level as well as between corresponding attention states across task levels. Bonferroni correction was applied. Results are summarized in Table 7.

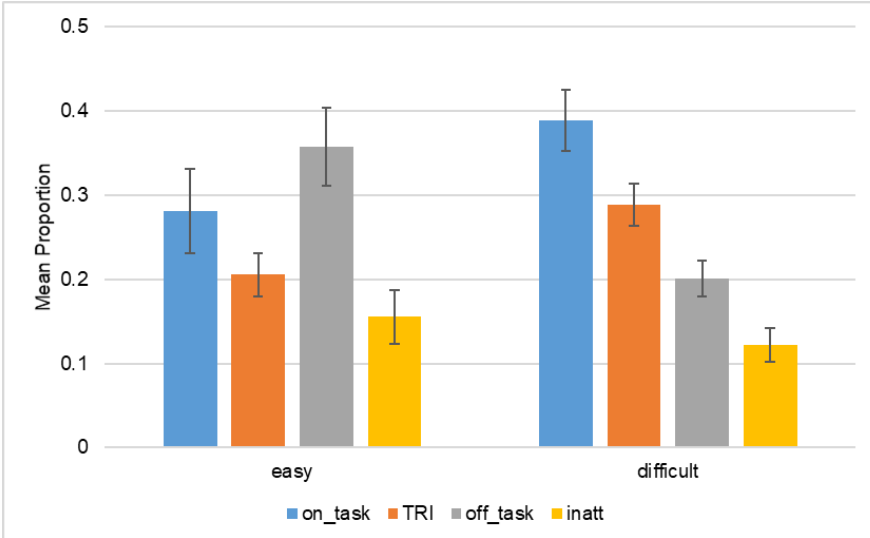

Figure 21 - Study 2, Prompt 1. Proportions of each attention state calculated within task level. There was a significant main effect of Prompt 1 and a significant interaction between Prompt 1 and task level.

Table 7 - Pairwise comparisons between proportions of the Prompt 1 attention states within each task level (Easy level and Difficult level) and between each task level.
***: Significant after Bonferroni correction**

	Pair		t-value	*p*-value
EASY LEVEL				
	on-task	- TRI	-1.038	.307
		- off-task	0.996	.327
		- inattentive	-1.622	.115
	TRI	- off-task	2.588	.015
		- inattentive	-1.028	.312
	off-task	- inattentive	-3.319	.002 *
DIFFICULT LEVEL				
	on-task	- TRI	-1.813	.08
		- off-task	-3.597	.001 *
		- inattentive	-5.809	< .001 *
	TRI	- off-task	-2.817	.008
		- inattentive	-5.145	<.001 *
	off-task	- inattentive	-2.809	.008
BETWEEN LEVELS				
	on-task easy	- on-task difficult	-3.264	.003 *
	TRI easy	- TRI difficult	-3.205	.003 *
	off-task easy	- off-task difficult	4.183	< .001 *
	inattentive easy	- inattentive difficult	0.886	.383

Prompt 2. The proportions of external and internal thoughts were calculated within task level out of the number of off-task thoughts. Paired t-tests were run for each comparison and Bonferroni correction was applied. In both task levels, there was a greater proportion of internal thoughts compared to external thoughts (Figure 22), both *t*s > 2.88, *p*s < .008. There was no significant difference between the proportion of external thoughts in the easy condition compared to the difficult condition, $t(31) = .957$, $p = .346$, and as consequence[2] there was no significant difference between the proportion of internal thoughts in the easy condition compared to the difficult condition. In addition, there was a significant difference when comparing external and internal proportions across task levels (i.e., external-easy vs internal-difficult and internal-easy vs external-difficult)[2], $t(31) = 4.71$, $p < .001$.

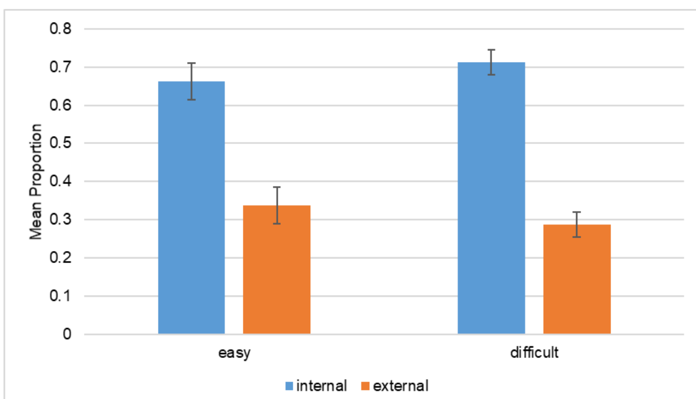

Figure 22 – Study 2, Prompt 2. Proportions of external and internal thoughts (out of total off-task thoughts) calculated within task level. Overall, there was a significantly greater proportion of internal thoughts compared to external thoughts.

[2] Note that because Prompt 2 is a binary condition and the proportions were calculated out of the number of off-task thoughts in each task level, the statistical tests here are comparable for both external and internal attention states when comparing across task levels (e.g., if the proportion of internal thoughts is .66, then the proportion of external thoughts must be .34).

Prompt 3. The proportions of spontaneous and constrained thoughts were calculated within task level out of the number of off-task thoughts (Figure 23). Paired t-tests were run for each comparison for a total of six comparisons. On average, there was a greater proportion of spontaneous thoughts in the difficult condition compared to the easy condition, however this did not reach significance, $t(31) = -1.74$, $p = .091$. (Note, however, that the overall number of reported off-task thoughts was lower in the difficult level; Figure 21). In addition, there was a greater proportion of constrained thoughts in the easy condition compared to the difficult condition, but as with the previous comparison[3], this was not significant, $t(31) = 1.74$, $p = .091$. There was a significant difference between the proportion of spontaneous and constrained thoughts within the difficult condition, $t(31) = 2.19$, $p = .036$, however, this did not survive Bonferroni multiple comparison correction. No other comparisons were statistically significant.

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[3] Note that because Prompt 3 is a binary condition and the proportions were calculated out of the number of off-task thoughts in each task level, the statistical tests here are comparable for both spontaneous and constrained attention states when comparing across task levels (e.g., if the proportion of spontaneous thoughts is .53, then the proportion of constrained thoughts must be .47).

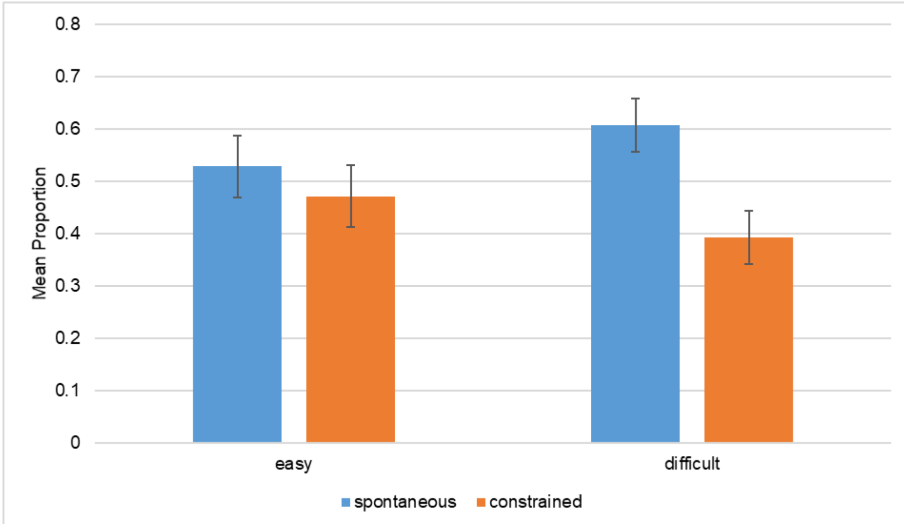

Figure 23 – Study 2, Prompt 3. Proportions of spontaneous and constrained thoughts (out of total off-task thoughts) calculated within task level. No comparisons survived multiple comparison correction. Without correction, there was a significantly greater proportion of spontaneous compared to constrained thoughts in the difficult condition.

3.2.2 Behavioral Data

Prompt 1. There was a significant main effect of attention state, $F(3, 192) = 3.329$, $p = .021$. Post-hoc comparisons using Tukey correction indicated that RRT variance was significantly greater for the inattentive attention state compared to on-task thoughts, $z = 3.01$, $p = .014$, and was marginally significantly greater compared to TRI thoughts, $z = 2.476$, $p = .064$. No other comparisons were significant, all $zs < 2.40$, all $ps > .100$. There was no significant main effect of task level, $F(1, 192) = 2.005$, $p = .158$, and there was no significant interaction between attention state and task level, $F(1, 192) = .895$, $p = .445$. Results are shown in Figure 24.

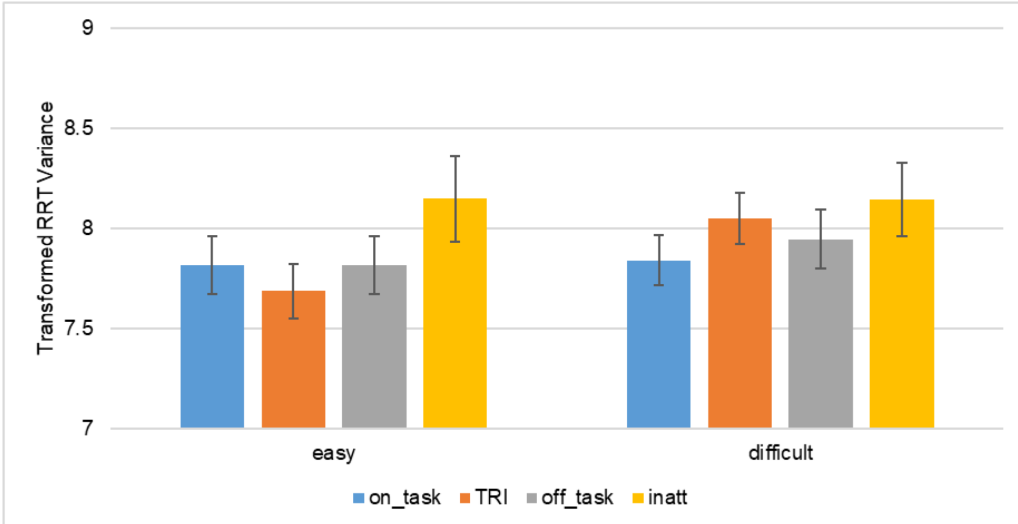

Figure 24 – Study 2, Prompt 1. Transformed RRT variance. There was a significant main effect of attention state, where RRT variance was greater for the inattentive state compared to on-task thoughts.

Prompt 2. There was a significant main effect of task level, $F(1, 65) = 4.326$, $p = .0415$, indicating that RRT variance increased overall during the difficult task level. The main effect of environment was not significant, $F(1, 65) = 2.245$, $p = .139$, and the interaction between task level and environment was not significant, $F(1, 65) = 1.926$, $p = .170$. Results are shown in Figure 25.

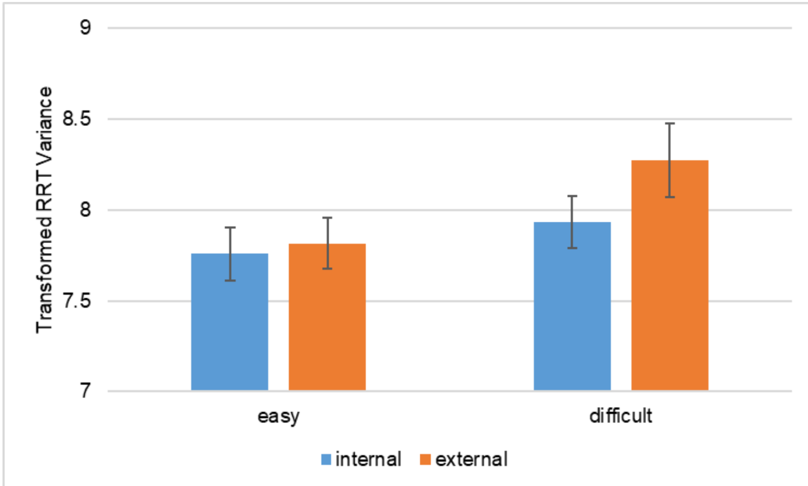

Figure 25 – Study 2, Prompt 2. Transformed RRT variance. Overall, RRT variance was significantly increased during the difficult task level.

Prompt 3. There were no significant main effects for task level, $F(1, 69) = 1.346$, $p = .250$, or for attention state, $F(1, 69) = 1.593$, $p = .211$. However, there was a significant interaction between task level and attention state, $F(1, 69) = 5.720$, $p = .020$. Post-hoc comparisons using Tukey correction indicated that within the easy task level, mean RRT variance was significantly greater for spontaneous thoughts than constrained thoughts, $z = 2.623$, $p = .044$. In addition, for constrained thoughts, mean RRT variance was marginally significantly greater in the difficult task condition than the easy task condition, $z = 2.536$, $p = .054$. No other post-hoc comparisons were significant (all *p*s > .299). Results are shown in Figure 26.

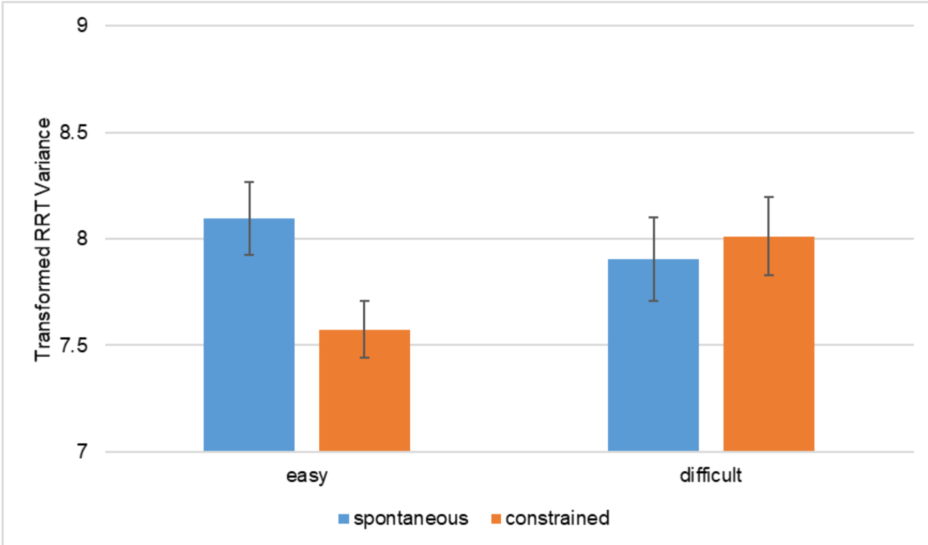

Figure 26 – Study 2, Prompt 3. Transformed RRT variance. There was a significant interaction between attention state and task level. Within the easy task level, RRT variance was significantly greater for spontaneous than constrained thoughts.

3.3 Summary and Discussion

The difficulty manipulation in Study 2 provided a way to examine performance variability and frequency of attention states as a function of cognitive load. Although performance variability did not differ significantly across the easy and difficult levels when examining the attention states of Prompt 1, overall performance accuracy of the tapping patterns was significantly different between the two task levels. In addition, participants reported that the difficult level was indeed more challenging subjectively compared to the easy level. This suggests that the cognitive load manipulation worked and that the difficult level was harder than the easy level.

As predicted, there was a greater proportion of off-task thoughts reported in the easy level compared to the difficult level. Conversely, as predicted, there was a greater proportion of on-task thoughts reported in the difficult level compared to the easy level.

However, there was no significant main effect of task level for RRT variability, indicating that performance variability was comparable between both the easy and difficult task levels. In addition, within the easy level, the pattern of monotonically increasing RRT variability observed in Study 1 did not replicate, despite the equivalence between the easy level of Study 2 and the task in Study 1. It is possible this result did not replicate due to a lack of power, as there were only four blocks, and thus a fewer number of trials, in the easy level of Study 2. However, it is also important to consider the context in which this task was performed. Study 2 consisted of both easy and difficult levels presented pseudo-randomly across eight blocks. The task overall was quite repetitive and unexciting. In particular, the easy level was very repetitive and required an increased amount of vigilance to maintain complete focus, whereas the difficult level was much more challenging. Some recent research has suggested that interspersing a boring task requiring vigilance with a more challenging task can provide the individual with a "break" that can increase arousal and improve performance on easy, vigilance-demanding tasks (Esterman & Rothlein, 2019). That may be similar to what occurred in this study. These ideas are further expanded upon in the Discussion.

There was a significant interaction in RRT variance between task level and thought dynamics. Within the easy task level, RRT variance was significantly greater for spontaneous thoughts compared to constrained thoughts. In addition, there was a relatively equal proportion of spontaneous and constrained thoughts reported within the easy task level. Furthermore, there were relatively more spontaneous thoughts compared to constrained thoughts reported in the difficult level, however this comparison did not reach significance after multiple comparison correction. In general, these patterns of attention state frequency and performance variability across task levels speak to the ideas proposed in the context regulation hypothesis (Smallwood & Andrews-Hanna, 2013). These patterns indicate that when cognitive load is increased, as in the difficult level, the tendency to experience constrained, off-task thoughts decreases, perhaps due to the need for executive control mechanisms to guide task performance rather than engage in off-task thought. When attention lapses during the difficult level, it may be the result of a failure in executive control measures, and thus spontaneous off-task thoughts are more frequently experienced. Although previous research has suggested that within low cognitive load tasks, strong performance can be maintained in the face of attention lapses (e.g., Levison et al., 2012), the RRT variance data here suggest that performance quality may actually be a function of the dynamics of the off-task thoughts of the individual. RRT variance was low in the easy condition particularly when the individual experienced constrained off-task thoughts. However, RRT variance increased and was comparable to that in the difficult condition when the individual experienced spontaneous off-task thoughts. The implications of these results and further interpretation within the context regulation hypothesis is addressed in the Discussion.

CHAPTER 4. DISCUSSION

The overarching goal of this work was to elucidate the behavioral characteristics and neural mechanisms of a broad range of attention states and their dynamics. Specifically, I aimed 1) to provide a clearer understanding of off-task thoughts and their dynamics relative to on-task thought and other forms of attention lapses; 2) to test the extent that performance and self-reported attention state are dissociable; and 3) to examine the effect of cognitive load on performance and attention state. To achieve this, I ran two studies and incorporated a multimodal set of cognitive neuroscience methods including behavioral performance, functional neuroimaging, pupillometry, and self-report measures. In Study 1, unique behavioral and neural correlates were observed across different attention states, and performance and attention state were dissociated. In addition, fMRI activation and functional connectivity differentiated spontaneous and constrained attention states and, as discussed below, provided the first empirical evidence of the dynamics of attention states proposed in the framework of Christoff et al. (2016). In Study 2, performance varied systematically between thought dynamics as cognitive load increased, further supporting the framework proposed by Christoff et al. (2016) and the context regulation hypothesis (Smallwood & Andrews-Hanna, 2013). Furthermore, across the results, a set of patterns emerged that speaks to a different perspective on mind wandering regarding task disengagement.

4.1 Behavioral Performance and Attention States

It is important that, in Study 1, results from Prompt 1 replicated those of Seli and colleagues (2013): RRT variance was significantly smaller during the on-task attention state compared to the off-task state, indicating that overall, performance decreased during the off-task state compared to on-task. Across all distraction prompts (TRI, off-task, and inattention), RRT variability increased compared to on-task, confirming that each of these attention states is a form of distraction when defined both subjectively and behaviorally. Overall, participants reported fewer instances of being in an inattentive state compared to on-task and the other forms of distraction, indicating that most of the time, participants were at least paying attention to something if not the task itself. In addition, the frequency of off-task thoughts was relatively steady across blocks, and frequencies were similar to those reported elsewhere (e.g., Unsworth & Robison, 2016).

Performance also differed between other pairs of distraction states, in particular the inattentive state. RRT variance was greater in this state compared to the TRI state. Similarly, RRT variance in the inattentive state was greater than in the off-task state; however, this effect did not reach significance . These findings provide support for the hypothesis that different forms of distraction have different effects on performance, perhaps as a function of task disengagement (discussed below). These findings also align with previous research that has documented similar relative decreases in performance during inattentive states (Unsworth & Robison, 2016). At the same time, these results indicate that other forms of distraction have similar consequences in terms of performance. Specifically, there was no difference in RRT variance between off-task and TRI thoughts. This result suggests that even when one is indirectly focused on the task (i.e., by thinking about topics related to the task), these thought processes can be similarly detrimental to performance.

More broadly speaking, RRT variance followed a nearly monotonic increase from on-task to inattentive. Although the attention states of Prompt 1 were defined categorically, the overall pattern is consistent with the concept of varying disengagement during task performance. For example, Cheyne et al. (2009) described mind wandering in terms of disengagement over the course of distinct states. These distinct states ranged from transient disengagement from a task where the individual can typically re-focus effectively and avoid overt errors, to full "decoupling" from the task where serious behavioral errors can occur. Another group of researchers (Schad, Nuthmann, & Engbert, 2012) proposed a levels of inattention hypothesis, which predicts that reductions in attention and other cognitive processes can occur at different hierarchical levels (e.g., early perceptual versus higher-order abstract processing). The attention state categories from Prompt 1 may have captured similar levels of disengagement ranging from full engagement (on-task) to severe decoupling (inattention).

To investigate more deeply the behavioral characteristics of attention, a second analysis was run on the raw RRT data where the ex-Gaussian parameters of each attention state in Prompt 1 were estimated. Here, *tau* was significantly greater for off-task and inattentive states compared to on-task and TRI states. In addition, *sigma* also varied between attention states, although the main effect did not quite reach significance. As illustrated in Figure 12, the distributions of the off-task and inattentive states are more positively skewed and characterized by heavier tails compared to the on-task and TRI states. In general, a greater proportion of these trials were higher overall in RRT variability.

Research has attributed the *mu* and *sigma* parameters to sensory-motor and automatic processes, whereas the *tau* parameter has been linked with higher-level controlled processes (Hohle, 1965). However, others have argued that it is not accurate to directly link cognitive processes to parameter values (Heathcote et al., 1991; Matzke & Wagenmakers, 2009). Nonetheless, understanding the distribution of data can help inform characteristics of these processes and guide theoretical development (e.g., Schmiedek et al., 2007). For example, the *tau* parameter and the slowest responses on performance tasks have been associated with diminished executive control and attention lapses (as indexed by reaction time; Unsworth, Redick, Lakey, & Young, 2010). Although previous research has linked lapses of attention to the *tau* parameter (and thus the slowest responses on a task), no studies have examined the ex-Gaussian distribution of performance variability across self-reported attention states as in the current study. The results here further demonstrate the tendency for RRT variance to increase from on-task to the inattentive state, as first indicated by the parametric analysis described earlier. In addition, the ex-Gaussian analysis provides descriptive value and insight into the mechanisms underlying each attention state. From these distributions, one can speculate about the mechanisms underlying these attention lapses. For example, the increased variability in performance variance across trials can reflect reduced efficiency in information processing (Hawkins, Mittner, Boekel, Heathcote, & Forstmann, 2015), perhaps due to increased disengagement from the task at hand (Cheyne et al., 2009). In contrast, the efficiency in information processing during on-task performance may be driven by stable engagement in the task at hand. Furthermore, the fact that in increased distraction states (viz. off-task and inattention states) performance variance is not just consistently increased compared to on-task but rather it itself varies across trials suggests that there is an increased volatility and unpredictability in the processes underlying these states.

4.2 Neural Correlates of Attention States

As in previous research, the fMRI whole brain analysis of the Prompt 1 attention states demonstrated increased activation in several DMN regions when participants were off-task or otherwise distracted. When collapsing across all forms of distraction, activation was observed across the brain and concentrated in several DMN regions, including the left inferior frontal gyrus and middle orbital/medial PFC. A small but significant cluster of activity was also observed in the left parahippocampul gyrus of the MTL during distraction states. Interestingly, and discussed further below, there was a large cluster of activation observed in the left motor regions.

Despite previous findings (Stawarczyk et al., 2011b), there was no significant activity in the TRI attention state compared to on-task. Furthermore, there was no significant activity in the TRI state when compared to the off-task state. This may be due to overlap in the processes occurring in the TRI state, which could be characteristic of either on-task and off-task, and thus the detection of unique TRI-related brain regions was hampered. The TRI state is characterized by thoughts related to the task, such as how well one is performing or the purpose of the task. Although specific thoughts likely varied across participants, the general nature of this attention state suggests that it may recruit a set of mechanisms consisting of frontoparietal control regions to guide evaluation and question formation as well as DMN regions to guide the generation of TRI thought content and related topics.

Using the on-task attention state for comparison, a conjunction analysis revealed similarities and differences between the off-task and inattentive states. Unique activity in the off-task state, which was not present in the inattentive state, was observed in a large set of DMN and MTL regions, including the precuneus, parahippocampal gyrus, and inferior frontal gyrus. Activation in the insula was also observed. Furthermore, a second conjunction analysis testing for unique activation in the off-task state compared to both the inattentive and on-task conditions found a significant cluster of voxels in the left middle frontal gyrus, part of the FPCN. Together, these results replicate many previous research studies that associated DMN regions with off-task thought and highlight the involvement of executive function regions in supporting off-task thought (Christoff et al., 2009). These results also emphasize the role these regions may have specifically in off-task thought in contrast to other forms of distraction (e.g., inattentiveness) or distraction in general.

Compared to on-task, both the off-task and inattention states yielded activation in the left inferior frontal gyrus and left ACC. In addition, unique to the inattentive state were patterns of activation in subregions of the ventral and dorsal ACC and left inferior frontal gyrus which were not overlapping with the off-task state. Whereas the ACC and IFG have been observed before during mind wandering, in the current research these regions were associated with the inattention state, a state which is likely further decoupled from the task and characterized by drowsiness or fatigue. In support of these findings, research linking fMRI with behavioral microsleeps during a vigilance task found increased activity in frontal and parietal regions, including the inferior frontal gyrus (Poudel, Innes, Bones, Watts, & Jones, 2014). The researchers speculated that this activity may be related to attempts to stay awake and restore responsiveness, as opposed to reflecting general drowsiness. A similar mechanism may have occurred in the participants of the current study. In addition, the ACC is a major node of the ascending arousal system (Poudel et al., 2014). Previous research linking BOLD signal with EEG-vigilance states found increased activation in the ACC and throughout the frontal cortex during the transition between wakefulness and sleep onset (Olbrich et al., 2009).

In mind wandering research, attention states have been typically dichotomized into on-task or off-task, although a growing amount of research has further examined the diverse contents and dynamics that characterize attention (Andrews-Hanna et al., 2017). However, explicitly asking participants about their experience of inattentiveness is less common. This comes in contrast to the likelihood that participants can indeed be drowsy during experiments, as reported in other studies (Unsworth & Robison, 2016). Differentiating between general inattentiveness and active, off-task thought is important both theoretically and in practice. The current study revealed that a subset of brain regions is associated with both off-task thought and inattentiveness, but that unique brain regions can be tied to each attention state.

Finally, activation over the left motor cortex was observed in both the off-task state and the inattentive state. Given that the MRT consisted of rhythmic tapping with the right index finger, this activity is likely reflective of the increased variability in these distraction states. Previous research also found increased fMRI activity in the left premotor cortex when attention lapses occurred in a behavioral task (Weissman, Roberts, Visscher, & Woldorff, 2006). Another group of researchers recorded functional near-infrared spectroscopy during a vigilance task and observed increased primary motor cortex activity as a function of time on task (Derosiere, Billot, Ward, & Perrey, 2013). The authors suggested that cognitive demand increases based on time on task and that the heightened motor activity reflects the engagement of certain brain regions (e.g., motor cortex) needed to cope with the increase in cognitive demand. Finally, a recent fMRI study examining fluctuations during performance of the gradCPT observed increased motor cortex activity preceding commission errors (Fortenbaugh, Rothlein, McGlinchey, DeGutis, & Esterman, 2018). In this case, the authors suggested that this activity could be related to a more pre-potent response set leading to a failure to inhibit the upcoming response. In the current research, this increased motor cortex activation could be related to a failure to inhibit out-of-sync MRT button-presses, or more generally, to periods of increased task demand (Derosiere et al., 2013).

4.3 Dissociation of Performance and Attention States

Overall, the MRT procedure demonstrated that, as predicted, RRT variance increased in distracted states and that this variance tended to increase as individuals lapsed further into distraction (e.g., inattentive state). Despite these overall patterns, there were still instances where participants reported being on task but their performance was relatively variable, and instances where participants reported being off task but their performance was relatively stable. Examining on-task and off-task attention states under conditions of high and low performance variability in the quadrant state analysis provided a more nuanced understanding of subjective and objective measures of attention and highlighted important considerations regarding subjectively and objectively-defined attention states.

Overall, as expected, performance was worse during the off-task attention state compared to on-task. However, by taking a closer look at the data, additional subtle but consistent differences between performance and attention state emerged. RRT variance during on-task thoughts was, on average, less variable than during off-task thoughts.

However, the variance of RRT during off-low thoughts was still significantly greater compared to that of on-low thoughts. Conversely, the RRT variance of on-high thoughts was significantly less compared to that of off-high thoughts. These comparisons indicate the unique contribution that on-task and off-task attention states have on performance. When an individual is off-task, even their best performance does not match that of being completely on-task (i.e., subjectively on-task and low performance variability). When an individual is on-task, even their worst performance is better than that of being completely off-task (i.e., subjectively off-task and high-performance variability).

Although these differences are small, these results may have important implications. For example, it may be the case that off-low and off-high reflect two distinct cognitive states. In support of this, a recent neural model of mind wandering (Mittner, Hawkins, Boekel, & Forstmann, 2016) proposed a conceptual distinction between 1) an off-focus state characterized by "tuning out" (e.g., Seli et al., 2013) where behavioral variability is moderately increased relative to on-task; and 2) an active mind-wandering state characterized by engagement with an internal stream of thought, where behavioral variability is highest relative to on-task. Perhaps the off-low condition in the current study corresponds with the off-focus state of Mittner et al. (2016), whereas the off-high condition corresponds with the active mind wandering state. From this model, it is not clear the implication of the on-high condition. However, in general one can speculate that it is possible that this condition reflects periods of task performance where participants noticed they were off-task, and actively concentrated on the task to attempt to steady their performance (similar to that described by Hasenkamp et al., 2012).

Alternatively, the behavioral results can be interpreted within the framework of the context regulation hypothesis (Smallwood & Andrews-Hanna, 2013). As discussed earlier, the context regulation hypothesis drives several predictions regarding performance and off-task thought. Specifically, when task demands are low, individuals often have the ability to lapse into mind wandering processes while maintaining steady performance. However, when task demands increase, performance tends to drop as one engages in mind wandering. Although the task demands of Study 1 were not explicitly manipulated, it is possible that participants perceived changes in cognitive demand as attention fluctuated (Kucyi et al., 2016a), perhaps as a function of the disengagement of sensory or cognitive networks needed to perform the task (Derosiere et al., 2013). If this is the case, then the off-high condition could indicate temporary increases in cognitive demand, where performance falters as an individual engages in off-task thought. Furthermore, the off-low performance instances could reflect a state in which task demands were low, and participants could engage in off-task thought with less detriment to performance.

What is particularly interesting is that these results are significantly different yet overall rather similar. That is, the RRT variance in the off-low condition was significantly greater than the RRT variance in the on-low condition. However, despite the difference, the sheer magnitude between off-low ($M = 7.22$) and on-low ($M = 6.87$) is very similar. This would not necessarily be expected in an off-task state, where performance variance would be predicted to be consistently and considerably larger compared to an on-task state given the numerous negative effects of distraction. For many intents and purposes, it may be sufficient to group the off-low performance into an overall "on-task" attention state defined behaviorally. Likewise, it may be sufficient to group the on-high performance into an overall "off-task" attention state defined behaviorally. Yet, by incorporating thought probes that specifically addressed on-task and off-task subjective attention states, subtle differences emerged that have interesting implications. Given that attention states fluctuate over the course of the task, could being in a subjective off-task state make it harder to transition to being fully on-task? Furthermore, is an individual more likely to further error when in a subjective off-task state, even if task performance is relatively stable? These are research questions that can be addressed to further understand the relationship between subjective attention states and performance.

Along with performance variability, neural activity was also examined in the quadrant state analysis. Although most whole-brain contrasts did not yield significant results, comparing off-high to on-high showed extensive activity throughout the brain in the off-high condition. Similar to the results of Prompt 1 described above, this activity was observed in areas belonging to the DMN as well as the FPCN, DAN, and motor cortex. Similar but less extensive results were observed when comparing activation in off-high to on-low.

The percent signal change analysis within the DMN provided a closer look at how activity in this network changed across the different conditions. As expected, overall there was increased DMN activity during the off-task state compared to on-task. In addition, although not significant, there was a trend in the interaction between attention state and performance. Interestingly, the pattern of results (Figure 19) is reminiscent of findings from Esterman et al. (2012) and Kucyi et al. (2016b). Both studies found increased DMN activity during periods of low performance variability in continuous tasks. Although the current results are not significant and should be interpreted cautiously, a trend suggests that both the on-low condition and off-low condition were associated with moderate levels of DMN activity relative to the other conditions. Similar to the interpretations provided by Esterman et al. (2012) and Kucyi et al. (2016b), this moderate amount of DMN activity may support the steady performance observed in both conditions, akin to an "in the zone" state where performance is optimal.

The research by Esterman et al. (2012) and Kucyi et al. (2016b) documented moderate amounts of DMN activity with stable behavioral performance. However, DMN activity has been consistently associated with mind wandering and corresponds with decreases in performance (Christoff et al., 2009; Andrews-Hanna et al., 2017). One goal of the current work in the quadrant analysis was to investigate these seemingly contradictory findings. Similar to this current work, Kucyi and colleagues (2016a) measured both behavioral variability and self-reported attention state throughout performance of the gradCPT. However, the current results did not replicate their findings. Kucyi et al. (2016a) found independent, additive effects of attention state and performance on DMN activity. In addition, they found the greatest amount of DMN activity in the off-task, stable performance condition whereas there was a moderate amount of DMN activity during both on-task, stable performance and off-task, variable performance. The authors suggested that these findings are evidence that DMN activity may independently reflect both mind wandering and stable performance, perhaps due to separate neurophysiological processes. In the current study, however, increased DMN activity was associated with the off-task state in general, and there was a trend in the interaction between attention state and performance. These data suggest that instead of independent neurophysiological processes, the DMN more broadly tracks general off-task processes, or, in the case of the trending interaction, that the role of the DMN is similar to that proposed by Esterman et al. (2012).

Mind wandering is a heterogenous phenomenon that can be described by many characteristics, including by a hierarchy of disengagement (e.g., Mittner et al., 2016, Cheyne et al., 2009) and by its dynamics (Christoff et al., 2016). In fact, in response to the study by Kucyi et al. (2016a), Csifcsak and Mittner (2017) suggested that one reason the researchers may have observed greater DMN activity in both self-reported mind wandering and stable behavior is that the predominant form of off-task thought in that study could have been the “off-focus” state of mind wandering described in the model of Mittner et al. (2016). Along with moderate increases in performance variability, this model states that off-focus mind wandering is characterized by increased activity in core regions of the DMN (e.g., the PCC and mPFC) and is more common in demanding tasks with complex stimuli, such as the gradCPT used by Kucyi et al. (2016a). Although a direct parallel between the model of Mittner et al. (2016) and the attention states of the current research cannot be drawn, it is important to note that in the off-task attention state participants reported both spontaneous and constrained thoughts as well as internally and externally-driven thoughts. Due to the small number of reports in each of the attention states of the quadrant analysis, it was not possible to further analyze them with respect to their dynamics or environment. However, overall, especially within the context of the simple MRT procedure, it is possible that participants experienced more variety of off-task thoughts in the current study than did the participants in Kucyi et al. (2016a). These findings further highlight the implications that mind wandering characteristics and task context have on elucidating the mechanisms supporting attention states.

The quadrant state analysis was designed to provide a more nuanced look at the relationship between performance variability and self-reported attention focus. The behavioral data demonstrate that, in general, performance variability increased during the off-task attention state compared to the on-task state. Paired contrasts in the whole-brain fMRI analysis also distinguished between off-task and on-task, particularly when off-task performance was most extreme (viz. high variability). Similarly, analysis of DMN percent signal change showed increased neural activity in the off-task state compared to the on-task state, thus replicating the multitude of previous studies that have documented this relationship between DMN and off-task states or mind wandering (Fox et al., 2015).

The behavioral results also provide indication for a small but significant dissociation between subjective attention state and performance. The pattern of behavioral performance here fits well with the model of disengagement proposed by Cheyne et al. (2009) and may simply reflect an extension of the four broad attention states examined in Prompt 1. However, the same pattern did not extend to DMN activity. There are several reasons why this may have occurred. One reason is that there may not have been enough power to detect further differences, as suggested by the trending but nonsignificant interaction. Because the on-task and off-task attention states were subsequently divided into high and low variability performance based on the upper and lower thirds of RRT data, there were a relatively few number of trials that went into analysis. In addition, the DMN was defined broadly, based on the parcellation of Yeo et al. (2011). However, as proposed by Mittner et al. (2016) and others (Andrews-Hanna et al., 2017), subsystems of the DMN along with other large-scale networks may drive differences in attention state and performance, whereas core DMN regions may be common to many off-task thoughts and attention states in general. In general, it is possible that neural activity as measured here provides a coarser assessment of off-task states in relation to behavior, where DMN activity tracks overall, general differences in on-task and off-task states. In contrast, the simple, continuous nature of the MRT procedure captures subtle but important fluctuations within attention states.

4.4 Environmental and Dynamic Characteristics of Off-Task Thoughts

When participants indicated that their attention was off-task, they were then prompted with two additional questions regarding the focus of their off-task thoughts. These prompts addressed the environmental orientation of their thoughts (whether the thoughts were internally or externally-focused) and the dynamics of their thoughts (whether the thoughts were spontaneous or constrained). These prompts provided a way to examine more detailed characteristics of off-task thoughts and potential interactions between them.

In general, there were too few externally-focused attention states reported to examine the neural correlates of dynamic and constrained external thoughts. Therefore, to examine the neural correlates of environmental orientation, a whole brain fMRI analysis was conducted to compare internal and external thoughts overall. To examine the neural correlates of thought dynamics, analysis was performed on just internally-focused spontaneous and constrained thoughts. In terms of environmental orientation, there were small but significant differences in the whole brain analysis between the internal and external attention states. In particular, external thoughts were associated with activity in the right anterior IPL and right insula, consistent with externally-oriented attention and saliency processing, respectively (Christoff et al., 2016). In addition, activation was observed for externally-focused attention in right Heschl’s gyrus. This is consistent with auditory processing and suggests that many externally-oriented thoughts were likely focused on surrounding sounds (e.g., the MRI scanner; Ellamil et al., 2016).

The framework proposed by Christoff et al. (2016) predicts that spontaneously directed thoughts are supported primarily by the medial temporal lobes and DMN regions. In line with this, functional connectivity analysis showed significant, positive connectivity in bilateral hippocampus during spontaneous thoughts. However, increased fMRI activation was observed in the left hippocampus for constrained thoughts as opposed to spontaneous thoughts. In addition, a small increase in functional connectivity across the DMN was observed for constrained compared to spontaneous thoughts. This is opposite of the original prediction one might have. Although it is not directly clear the mechanisms these patterns represent, it is possible that the increased DMN functional connectivity during constrained thoughts reflects an increased level of homogeneity in processing across the network, perhaps driven by another set of brain regions or networks. For example, previous research found increased functional connectivity between the DMN and FPCN during autobiographical planning but found increased functional connectivity between the FPCN and DAN during visuospatial planning (Spreng et al., 2010). Building on this, a previous functional connectivity study incorporating graph theory analytics found that the FPCN was functionally interposed between the DMN and the DAN (Spreng, Sepulcre, Turner, Stevens, & Schacter, 2013). In support of this in the current study, there was a marginal yet non-significant increase in connectivity between the DMN and FPCN during constrained thoughts, suggesting that to a small degree, the two networks function coherently to drive certain attention states. Finally, although increased connectivity was observed in the bilateral hippocampus during spontaneous thoughts, DMN connectivity overall was decreased relative to FPCN connectivity during spontaneous thoughts. Similar to above, it is possible that this pattern reflects the variable, dynamic processing in the DMN that is needed to drive the spontaneous thoughts (Ellamil et al., 2016). In general, these results provide the first empirical evidence of the dynamics of attention states as predicted by previous theorizing (Christoff et al., 2016).

Pupil diameter measurements also showed interesting patterns across spontaneous and constrained attention states. There was a significant interaction between environment and dynamics. Specifically, within the internally-focused attention state, the average size in pupil diameter was smaller for spontaneous thoughts compared to constrained thoughts, the latter which was comparable in size to the baseline period. Spontaneous thoughts can be described as mental states that arise freely, and where the transitions between content flow with little effort (Christoff et al., 2016). In addition, Lenartowicz et al. (2013) argue that the effect of the LC-NE system drives different qualities of thought based on arousal level. Specifically, Lenartowicz et al. state that low arousal may be associated with mind wandering, where thoughts drift from one topic to another similar to the characteristics of spontaneous thought described by Christoff et al. (2016). Given that pupil diameter has been shown to follow an inverted-U shape in relation to attention and arousal (Aston-Jones & Cohen, 2005), the decrease in pupil diameter observed here during spontaneous thoughts may correspond to an overall change from constrained, focused periods of thought to the dynamic, effortless form of spontaneous thought that may occur during lower levels of arousal (Unsworth & Robison, 2018). Furthermore, pupil diameter of the constrained attention state did not change from baseline, suggesting that the constrained attention state reflects an arousal level similar to that during baseline, when participants are likely focused and constrain their thoughts in preparation for the upcoming trial.

Finally, there were no significant differences in RRT variability within environments or dynamics, nor was there a significant interaction between the two. Regardless of the orientation of one's off-task thought, performance was not affected. Although this null result does not rule out the possibility that behavioral performance differs between these attentions states in other contexts (see Study 2), the findings here demonstrate how an integrative, multimodal approach in neuroscience can elucidate differences between cognitive processes. Although RRT variance did not differ across environments or dynamics in Study 1, pupil diameter and BOLD signal metrics helped begin to clarify the neural mechanisms of thought dynamics.

4.5 Cognitive Load, Attention States, and Performance

A number of emerging studies have implicated the role that task difficulty may have on mind wandering (e.g., Levinson et al., 2012). Although it is rather unsurprising that mind wandering increases during easy tasks, some studies suggest that certain characteristics of off-task thought, such as intentionality, may be more prominent under some task conditions than others (Seli et al., 2016, Seli, Risko, Smilek, & Schacter, 2016b). In addition, the context regulation hypothesis (Smallwood & Andrews-Hanna, 2013) makes predictions regarding the role of executive function in mind wandering that can be tested across levels of cognitive demand. Study 2 provided a way to test directly the effect of cognitive load on attention states and performance. Here, task difficulty was manipulated by changing the tapping patterns. The easy condition simply required participants to tap in sync to the metronome as in Study 1. The difficult condition required participants to perform two different tap patterns based on the pitch of the metronome, which could change randomly throughout each tap period. As expected, more off-task thoughts were reported during the easy condition compared to the difficult condition, and more on-task thoughts were reported during the difficult condition compared to the easy condition. Relatedly, off-task thoughts comprised the majority of the Prompt 1 attention states in the easy condition, and on-task thoughts comprised the majority of the attention states in the difficult condition.

In the context regulation hypothesis, Smallwood and Andrews-Hanna (2013) propose that the role of executive function in mind wandering varies as a function of the relative demands of the external task. When the task is difficult, executive control is used to drive task processing and minimize mind wandering. When the task is easy, executive control may maximize the occurrence of off-task thought. Since constrained thoughts are thought to largely be supported by executive function and the FPCN (Christoff et al., 2016), it stands to reason that these types of off-task thoughts are more prevalent in easy tasks. The rates of each type of off-task thought dynamic in Study 2 begin to suggest this pattern. In Study 2, visual inspection of Figure 23 indicates that the easy condition yielded relatively more constrained thoughts (M = 47%) compared to the difficult condition (M = 39%). In addition, spontaneous thoughts were more frequent than constrained thoughts within the difficult level (M = 61% vs M = 39%). However, these results did not quite reach statistical significance and should be interpreted cautiously. Furthermore, performance variance also changed as a function of task level and thought dynamic. Specifically, within the easy condition, mean RRT variance was lower for constrained thoughts than spontaneous thoughts. In addition, when experiencing constrained thoughts, there was a trend for RRT variance to increase in the difficult task condition than the easy task condition.

Within the easy condition, mean RRT variance was lower for constrained thoughts than spontaneous thoughts. Conversely, there was no difference in RRT variance between the spontaneous and constrained attention states within the difficult condition. In other words, participants performed better in the easy condition when experiencing constrained thoughts relative to spontaneous thoughts, and they performed equally poorly in the difficult condition when experiencing either type of thought state. Furthermore, there was no significant difference between RRT variance of spontaneous thoughts in the easy condition and both spontaneous and constrained thoughts in the difficult condition. As discussed above, the context regulation hypothesis has implicated that under easy task conditions, individuals often mind wander because they can do so with little detriment to their performance (Smallwood & Schooler, 2015). However, the results here illustrate that it may not be mind wandering in general that drives this relationship with performance. Rather, the dynamics of the thought one is engaged in is strongly related to performance during a task, particularly when the task is easy. In this case of low cognitive load, constrained thought is associated with steady, less variable performance, whereas spontaneous thought is associated with more variable performance. Although it is not clear the mechanism behind this distinction, it is possible that little executive control was needed to implement the task in the easy condition, and thus the executive control that was allocated could drive off-task, constrained thought, somewhat like a dual-task process (Andrews-Hanna et al., 2017). Periodically executive control may drop, thus resulting in diminished performance as well as increases in spontaneous off-task thought (McVay &

Kane, 2010). Given the increased need for executive control to perform the task in the difficult condition, both forms of off-task thought were associated with worse performance. Overall, these results provide support for both the context regulation hypothesis and the framework of Christoff et al. (2016), as well as provide new evidence for how specific dynamics of off-task thought may affect performance.

Regarding the environmental orientation of off-task thoughts, internal thoughts were relatively more frequent than external thoughts in both the easy and difficult conditions. This replicates the overall findings in Study 1 as well as previous work that has observed relatively more internally-oriented thoughts during off-task states (Unsworth & Robison, 2016). In general, this result is not surprising given the stable, uninspiring external environment in which participants completed the experiment. Analysis of behavioral performance across the Prompt 1 attention states showed that RRT variance was increased across task levels during the inattentive condition relative to on-task. However, unlike in Study 1, there was no significant difference in RRT variance between the on-task attention state and either the TRI or the off-task state. In addition, in Study 2, there was a significant difference in RRT variance between spontaneous and constrained attention states in the easy task level. However, there were no differences in RRT variance between these attention states in Study 1, even though the tasks were the same. What could account for these differences? Although the MRT procedure itself was the same for Study 1 and the easy condition of Study 2, other factors may have influenced performance across the tasks. Study 1 was run in the MRI scanner, and additional instructions were given to participants to remain very still and to keep focus on the center of the screen at all times for eye tracking. These situations may have made the overall task more challenging. In support of this, the overall RRT variance was slightly, but not significantly, greater in Study 1 than the easy condition of Study 2. Another interesting perspective comes from research on vigilance and intervening tasks (Esterman & Rothlein, 2019). In a study by Ralph, Onderwater, Thomson, and Smilek (2017), participants performed a vigilance task either continuously or interspersed with either a break or a challenging visuospatial task. The researchers found that both the break and the challenging task alleviated the vigilance decrement in RT, suggesting that highly demanding tasks can enhance effortful processing across other conditions, perhaps by increasing general arousal (Ralph et al., 2017). A similar effect may have occurred in Study 2, where the difficult level provided a "break" from the monotony of the easy level. In general, the current results support the evidence that off-task thought is a heterogenous construct and its characteristics and implications in performance can be modulated based on the task at hand (e.g., Unsworth & Robison, 2018).

4.6 General Discussion

The current set of studies incorporated a simple performance task with multimodal cognitive neuroscience methods to investigate attention lapses. Two major sets of results emerged from this investigation along performance and dynamics. Regarding performance, RRT variance dissociated several different forms of attention lapses (e.g., inattention, off-task thought) and highlighted subtle but important distinctions between subjective attention reports and behavioral performance. Namely, on-low thoughts were consistently associated with decreased variance compared to off-low thoughts. Similarly, off-high thoughts were consistently associated with increased variance compared to on-high thoughts. Regarding dynamics, unique patterns of BOLD signal and pupil diameter were identified for spontaneous and constrained thoughts. For example, pupil diameter during spontaneous thoughts was significantly smaller compared to constrained thoughts with respect to baseline. In addition, functional connectivity was observed between the bilateral hippocampal regions during spontaneous thoughts. These behavioral and brain imaging differences offer a novel way to characterize the dynamics of off-task thoughts, which up until now research has ignored. Investigation of these dynamics in Study 2 provided further insight into how cognitive load can affect attention lapses and task performance.

One goal of this study was to isolate patterns of neural activity specific to each state in the quadrant state analysis. A set of predictions was made based on assumed levels of cognitive demand that fluctuated across each state. For example, the off-low condition could have reflected periods of low cognitive load when participants could mind wander with little detriment to task performance. In these instances, interactions between the DMN and FPCN should be observed. The off-high condition could have reflected periods of increased cognitive demand where performance declines when mind wandering occurs, and increased DMN activity would be observed. However, these predictions were not supported by the data. Instead, DMN percent signal change increased in off-task thoughts overall compared to on-task thoughts. In addition, there were no differences between the on-low and off-low conditions in the whole brain analysis, including within the DMN or FPCN. However, there was increased activity across the brain, including the DMN and a range of "task positive" brain regions, in the off-high condition compared to the on-low condition. Although it is possible that the relatively small sample sizes within each condition may have limited the results, it is clear that the original hypotheses are not supported.

An issue arising from the predictions above is that they were generated post-hoc, and that the differences in cognitive demand were merely assumed yet not actually manipulated. Although it is possible that cognitive demand inherently fluctuates across task even when the task itself is constant (Derosiere et al., 2013), the results from Study 2 suggest this may be less likely than originally considered. For example, in the difficult condition of Study 2, participants reported relatively more spontaneous thoughts than constrained thoughts, a finding that is in line with the context regulation hypothesis (Smallwood & Andrews-Hanna, 2013). If cognitive load did vary between the off-low and off-high conditions of Study 1, then it would be likely that the proportion of these attention states would too. However, across the four quadrants of Study 1, the proportion of spontaneous and constrained thoughts was consistent between the off-low (M_{spont} = .634, SEM_{spont} = .04) and off-high conditions (M_{spont} = .629, SEM_{spont} = .05).

A different approach to understanding performance and off-task thought is from the perspective of task engagement. The idea that off-task thought is characterized by perceptual decoupling has been addressed in previous research (Smallwood et al., 2011), and a recent model builds on this idea by organizing attention across three states: on-task, off-focus, and active mind wandering (Mittner et al., 2016). These attention states further correspond with the task engagement levels proposed by Cheyne et al. (2009) and with the distinction between "tuning out" versus "zoning out" in previous mind wandering literature (Seli et a., 2013). The current study did not explicitly ask participants regarding their level of engagement across the task. Therefore, it is unclear the true extent to which they were engaged at any given time. However, the distinctions outlined by Mittner and colleagues (2016) align nicely with the differences in RRT variance observed in the quadrant analysis, along with the monotonic pattern of behavioral performance across the Prompt 1 attention states in Study 1. Future research could measure or actively manipulate the level of engagement throughout tasks to study these processes further.

In general, people engage in off-task thoughts when the topics of those thoughts are more attractive or compelling than the task that one is performing (Mittner et al., 2016). The mechanisms supporting these thoughts as well as the task at hand are driven by a complex set of processes that likely involve a dynamic balancing between cognitive representations (e.g., task files; Bezdek, Godwin, Smith, Hazeltine, & Schumacher, 2018) of one’s current goals, interests, and concerns (Klinger, 1999; Klinger, Marchetti, & Koster, 2018; McVay & Kane, 2010). As described in Bezdek et al. (2018), over the course of cognitive processing, these representations compete with each other to further drive mental contents and behavior. In this sense, one’s “off-task” thoughts may very much be considered “on-task” to the individual if these thoughts align with the individual’s true goals and not the task at the moment. Content related to these “on-task” thoughts may be driven spontaneously, perhaps by neural mechanisms within the hippocampus and medial temporal lobes (Ellamil et al., 2016). In this sense, executive function is important for minimizing the occurrence of such intrusions and maintaining focus on the task at hand (McVay & Kane, 2010). However, once an individual lapses into off-task (or, “on-task”) thought (whether intentionally or unintentionally; Seli et al., 2016), the extent to which executive control is used to guide these thoughts in a directed manner can depend on the task demands itself (e.g., some tasks do not require much executive control) and perhaps the extent to which one remains engaged in the task. As demonstrated in Study 2, the difficult task level resulted in a relative drop in the proportion of constrained compared to spontaneous attention states, and performance quality suffered when constrained thoughts were experienced in the difficult level. While this is predicted by the context regulation hypothesis, a more general perspective of the relation between off-task thought and performance can be gained by thinking of off-task thought as encompassing one of many goals of the individual (Bezdek et al., 2018, Klinger et al., 2018), the extent to which one engages in the task or in off-task thought, and the roles that executive control can serve during performance (McVay & Kane, 2010; Smallwood & Schooler, 2006).

An overarching goal of Study 1 was to apply a triangulation approach to study attention lapses by incorporating complementary cognitive neuroscience methodologies: behavioral performance, fMRI, pupillometry, and self-report. Combined, these methodologies helped elucidate the neural correlates of attention states, albeit to different extents. When examining the attention states of Prompt 1, both behavioral performance and BOLD signal in fMRI uniquely characterized several attention states. In addition, despite the lack of behavioral differences, unique BOLD signatures were found for both environmental and dynamic characteristics of off-task thought, and the dynamics of thought were further characterized by differences in functional connectivity. Although there were no differences in pupil diameter across the four attention states of Prompt 1, pupil diameter differentiated internally-focused spontaneous and constrained thoughts in line with hypotheses regarding off-task thought and arousal (Lenartowicz et al., 2013).

Triangulation can be a powerful method in neuroscience. This is especially the case in areas of research such as mind wandering. Converging results across different methodologies provide support for characteristics of attention lapses that are otherwise only reported subjectively (Smallwood & Schooler, 2015). Together, the multimodal set of results from Study 1 help to further outline the characteristics that attention states can take. Although this provides important value from a descriptive viewpoint, this multimodal approach also provided an opportunity to test different theories and frameworks of mind wandering, such as the brain mechanisms supporting thought dynamics and the effect of task demand.

Not all methods yielded significant differences across comparisons, suggesting that some methods might be more sensitive to certain facets of attention lapses than others. Alternatively, it may be the case that there are different or more subtle features that should be analyzed within these methods. For example, use of MVPA has grown quickly in recent years due to its multivariate analysis approach to fMRI data. Studies have suggested that MVPA may be more sensitive compared to other analyses with respect to detecting cognitive states (e.g., Serences & Saproo, 2012). Furthermore, applying classifiers to multimodal data can provide further insight to mind wandering. For example, Mittner et al. (2014) incorporated features from fMRI and pupil diameter into a support vector machine classifier to predict self-reported mind wandering scores. In this analysis, the researchers found that a set of features consisting of fMRI activation and functional connectivity in the default mode and task-positive networks along with pupil diameter provided the best classification results.

The MRT procedure used in these studies provided a simple, continuous measure of behavioral performance. As discussed earlier, this simple method overcomes many of the limitations that tasks such as the SART have in terms of response selection and other additional cognitive processes. Therefore, the MRT provided a cleaner context in which to study the unfolding of attention states and distractions. In addition, incorporating the MRT provides a perspective on mind wandering from a context different from the typical go/no-go inhibitory tasks (e.g., SART, gradCPT) that have frequently been used to study off-task thought. However, it is uncertain the extent to which this task can generalize. The effects of distraction on performance as well as the neural and physiological correlates of off-task thought can be task-dependent. For example, there were no differences in pupil diameter across the four attention states of Prompt 1, despite previous research documenting differences in similar attention states (Unsworth & Robison, 2016). It may be the case that the MRT generalizes well to other tasks that are simple and continuous in nature. On the other hand, other results from this current work do illustrate the generalizability of the MRT procedure. Most prominently, increased RRT variance was observed across distraction states. This replicates not just research that has used the MRT previously (Seli et al., 2013), but also research that uses response inhibition tasks including the gradCPT (Esterman et al. 2012; Kucyi et al., 2016a) and SART (Bastian & Sackur, 2013). In addition, the current work, and much of the reviewed literature here, approached attention states from a general population perspective. However, there is large variability across individuals in terms of their ability to focus and tendencies to mind wander (Godwin et al., 2017). Individual differences such as working memory capacity (Levinson et al., 2012) and state characteristics such as current motivation and interest (Kane et al., 2017; Seli, Cheyne, Xu, Purdon, & Smilek, 2015) can play substantial roles in the occurrence of mind wandering and its effect on performance. Ultimately, a complete understanding of off-task thoughts, their effect on performance, and their neural mechanisms will be generated from a range of diverse contexts, measures, and individuals.

Attention lapses are multi-faceted and studying them is complex. The pattern of behavioral performance in Study 1 strongly suggests that mind wandering and attention lapses should be considered from a perspective of disengagement. Although disengagement was not directly measured or manipulated here, the monotonic increase in RRT variance from on-task to the inattentive state indicates increasing disengagement similar to that described by others (e.g., Cheyne et al., 2009). This perspective may prove increasingly fruitful in understanding the neural mechanisms of off-task thought (e.g., Mittner et al., 2016) and helps move away from the content-based mind wandering approach that has been criticized by others (e.g., Christoff et al., 2016). Investigation of the dynamics of mind wandering in the current studies yielded novel neuroimaging findings and theoretically-relevant behavioral results. Incorporating measures of thought dynamics, that is, the extent to which information processing occurs in a spontaneous or constrained manner, has important implications for understanding the role of brain regions and large-scale networks, as demonstrated with the current data. Ultimately, approaching mind wandering research from a combination of task disengagement and the ongoing cognitive and neural dynamics can provide tangible research goals and a more complete understanding of the complex, multi-faceted nature of mind wandering.

Last, it is important to comment on some of the real-world implications of this research. Although the studies conducted here were laboratory studies designed to examine aspects of attention and performance within an experimental setting, there is also significance to applied settings. Mind wandering has traditionally been considered a negative consequence of executive control failures, resulting in increased performance variability and errors. This was observed in the current data as well. However, emerging research argues that there are benefits to mind wandering. In addition, the data in Study 2 speak to the idea that the dynamics of off-task state may ultimately determine whether performance is as detrimental as typically considered. Moving forward, researchers and applied scientists should consider the implications of task context, disengagement, and thought dynamics in real-world applications. In the future, we may ultimately be able to develop teaching methods, therapeutic approaches, and incorporate various environmental settings that minimize detrimental instances of mind wandering and encourage beneficial mind wandering experiences for improved performance and well-being.

APPENDIX A. ATTENTION STATE DEFINITIONS AND EXAMPLES

Below is the script that is read to participants so they can learn about the different off-task thought states. Most of these examples were taken from Christoff et al. (2016). The examples illustrate how external/internal and constrained/spontaneous are independent dimensions, and thoughts can be either external or internal AND constrained or spontaneous.

When we are thinking about things other than the task we're doing, it's possible for our thoughts to be oriented either 'externally' or 'internally'. Externally-oriented thoughts are focused on things surrounding us in our environment, such as sights, sounds, smells, and bodily sensations (hunger/thirst/temperature). Internally-oriented thoughts are focused on things in our mind, such as thinking about the upcoming weekend or your last vacation.

Here are some examples:

Internally-oriented:

-While re-painting the walls of their room, a person plans their afternoon, figuring out how to combine multiple errands into a single car ride

-Despite their best attempts to write a paper, a student keeps fixating on a harsh comment from their teacher

- While driving in their car, a writer suddenly thinks of a line for the book they are writing, then remembers that they must pick up dog food on the way home, before reminiscing about the winters of their childhood

Externally-oriented:

-to stay awake during a boring lecture, a student tries to estimate who has the most expensive shoes in the room

-While listening to harsh criticism by the teacher, a student starts counting the tiles on the floor of the classroom as a means to stop from crying

-While studying in a quiet library, a student finds himself unable to ignore a buzzing fly

-While hiking on a forest trail, a hiker's thoughts move from the gravel on the path to a slug crawling up a stump, and then to a leaf floating in a puddle

In addition, when we are thinking about things other than the task we're doing, it's possible for our minds to move about 'freely' or for our thoughts to be 'constrained'. When thoughts move about freely, thinking may appear more spontaneous and may jump from one content to another. When our thoughts are constrained, thinking may feel more deliberate or goal-directed, or driven by a particular topic, concern, or stimulus.

Here are some examples:

Freely-moving:

- While driving in their car, a writer suddenly thinks of a line for the book they are writing, then remembers that they must pick up dog food on the way home, before reminiscing about the winters of their childhood *(internal)*

-While hiking on a forest trail, a hiker's thoughts move from the gravel on the path to a slug crawling up a stump, and then to a leaf floating in a puddle *(external)*

-As the child gazes out the window on the long plane flight, his thoughts drift from the clouds to the soothing motion of the plane, to the taste of ice cream leftover from a snack earlier *(external)*

-While cleaning the kitchen, a student daydreams about their upcoming weekend getaway, and then thinks about the midterm exam they took the day before, and then remembers they should give their parents a call before leaving *(internal)*

Constrained:

-While re-painting the walls of their room, a person plans their afternoon, figuring out how to combine multiple errands into a single car ride *(internal)*

-While studying in a quiet library, a student finds himself unable to ignore a buzzing fly *(external)*

-Despite their best attempts to write a paper, a student keeps fixating on a harsh comment from their teacher *(internal)*

-While listening to harsh criticism by the teacher, a student starts counting the tiles on the floor of the classroom as a means to stop from crying *(external)*

REFERENCES

Andrews-Hanna, J.R., Irving, Z.C., Fox, K.C.R., Spreng, R.N., & Christoff, K. (2018). The Neuroscience of Spontaneous Thought: An Evolving, Interdisciplinary Field. *The Oxford Handbook of Spontaneous Thought*, Fox, K.C.R., & Christoff, K (editors). Oxford University Press, United States

Andrews-Hanna, J. R., Reidler, J. S., Huang, C., & Buckner, R. L. (2010). Evidence for the default network's role in spontaneous cognition. *Journal of Neurophysiology*, *104*(1), 322-335.

Andrews-Hanna, J. R., Reidler, J. S., Sepulcre, J., Poulin, R., & Buckner, R. L. (2010). Functional-anatomic fractionation of the brain's default network. *Neuron*, *65*(4), 550-562.

Andrews-Hanna, J. R., Smallwood, J., & Spreng, R. N. (2014). The default network and self-generated thought: component processes, dynamic control, and clinical relevance. *Annals of the New York Academy of Sciences*, *1316*(1), 29-52.

Antrobus, J. S. (1968). Information theory and stimulus-independent thought. *British Journal of Psychology*, *59*(4), 423-430.

Antrobus, J. S., Coleman, R., & Singer, J. L. (1967). Signal-detection performance by subjects differing in predisposition to daydreaming. *Journal of Consulting Psychology*, *31*(5), 487.

Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance. *Annu. Rev. Neurosci.*, *28*, 403-450.

Bastian, M., & Sackur, J. (2013). Mind wandering at the fingertips: automatic parsing of subjective states based on response time variability. *Frontiers in Psychology*, *4*, 573.

Bezdek, M.A., Godwin, C.A., Smith, D.M., Hazeltine, E., & Schumacher, E.H. (in press) How Conscious and Unconscious Aspects of Task Representations Affect Dynamic Behavior in Complex Situations. *Psychology of Consciousness: Theory, Research, and Practice*

Cheyne, J. A., Solman, G. J., Carriere, J. S., & Smilek, D. (2009). Anatomy of an error: A bidirectional state model of task engagement/disengagement and attention-related errors. *Cognition*, *111*(1), 98-113.

Christoff, K. (2012). Undirected thought: neural determinants and correlates. *Brain*

Research, *1428*, 51-59.

Christoff, K., Gordon, A. M., Smallwood, J., Smith, R., & Schooler, J. W. (2009). Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proceedings of the National Academy of Sciences*, *106*(21), 8719-8724.

Christoff, K., Irving, Z. C., Fox, K. C., Spreng, R. N., & Andrews-Hanna, J. R. (2016). Mind-wandering as spontaneous thought: a dynamic framework. *Nature Reviews Neuroscience*.

Costa, V. D., & Rudebeck, P. H. (2016). More than meets the eye: the relationship between pupil size and locus coeruleus activity. *Neuron*, *89*(1), 8-10.

Csifcsák, G., & Mittner, M. (2017). Linking brain networks and behavioral variability to different types of mind-wandering. *Proceedings of the National Academy of Sciences*, *114*(30), E6031-E6032.

Derosière, G., Billot, M., Ward, E. T., & Perrey, S. (2013). Adaptations of motor neural structures' activity to lapses in attention. *Cerebral Cortex*, *25*(1), 66-74.

Dixon, M. L., Andrews-Hanna, J. R., Spreng, R. N., Irving, Z. C., & Christoff, K. (2016). Anticorrelation between default and dorsal attention networks varies across default subsystems and cognitive states. *bioRxiv*, 056424.

Dixon, M. L., Fox, K. C., & Christoff, K. (2014). A framework for understanding the relationship between externally and internally directed cognition. *Neuropsychologia*, *62*, 321-330.

Ellamil, M., Dobson, C., Beeman, M., & Christoff, K. (2012). Evaluative and generative modes of thought during the creative process. *Neuroimage*, *59*(2), 1783-1794.

Ellamil, M., Fox, K. C., Dixon, M. L., Pritchard, S., Todd, R. M., Thompson, E., & Christoff, K. (2016). Dynamics of neural recruitment surrounding the spontaneous arising of thoughts in experienced mindfulness practitioners. *Neuroimage*, *136*, 186-196.

Esterman, M., Noonan, S. K., Rosenberg, M., & DeGutis, J. (2012). In the zone or zoning out? Tracking behavioral and neural fluctuations during sustained attention. *Cerebral Cortex*, *23*(11), 2712-2723.

Esterman, M. & Rothlein, D. (2019). Models of sustained attention. *Current Opinion in Psychology*, *29*, 174-180.

Feng, S., D'Mello, S., & Graesser, A. C. (2013). Mind wandering while reading easy and difficult texts. *Psychonomic Bulletin & Review*, *20*(3), 586-592.

Forster, S., & Lavie, N. (2009). Harnessing the wandering mind: The role of perceptual load. *Cognition, 111*(3), 345-355.

Fortenbaugh, F. C., Rothlein, D., McGlinchey, R., DeGutis, J., & Esterman, M. (2018). Tracking behavioral and neural fluctuations during sustained attention: A robust replication and extension. *Neuroimage, 171*, 148-164.

Fox, M. D., Snyder, A. Z., Vincent, J. L., Corbetta, M., Van Essen, D. C., & Raichle, M. E. (2005). The human brain is intrinsically organized into dynamic, anticorrelated functional networks. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(27), 9673-9678.

Fox, K. C., Spreng, R. N., Ellamil, M., Andrews-Hanna, J. R., & Christoff, K. (2015). The wandering brain: Meta-analysis of functional neuroimaging studies of mind-wandering and related spontaneous thought processes. *NeuroImage*, *111*, 611-621.

Franklin, M. S., Broadway, J. M., Mrazek, M. D., Smallwood, J., & Schooler, J. W. (2013). Window to the wandering mind: Pupillometry of spontaneous thought while reading. *The Quarterly Journal of Experimental Psychology*, *66*(12), 2289-2294.

Gerlach, K. D., Spreng, R. N., Gilmore, A. W., & Schacter, D. L. (2011). Solving future problems: default network and executive activity associated with goal-directed mental simulations. *Neuroimage*, *55*(4), 1816-1824.

Gilzenrat, M. S., Nieuwenhuis, S., Jepma, M., & Cohen, J. D. (2010). Pupil diameter tracks changes in control state predicted by the adaptive gain theory of locus coeruleus function. *Cognitive, Affective, & Behavioral Neuroscience*, *10*(2), 252-269.

Godwin, C. A., Hunter, M. A., Bezdek, M. A., Lieberman, G., Elkin-Frankston, S., Romero, V. L., ... & Schumacher, E. H. (2017). Functional connectivity within and between intrinsic brain networks correlates with trait mind wandering. *Neuropsychologia*, *103*, 140-153.

Gruberger, M., Simon, E. B., Levkovitz, Y., Zangen, A., & Hendler, T. (2011). Towards a neuroscience of mind-wandering. *Frontiers in human neuroscience*, *5*, 56.

Gusnard, D. A., & Raichle, M. E. (2001). Searching for a baseline: functional imaging and the resting human brain. *Nature Reviews Neuroscience*, *2*(10), 685.

Hasenkamp, W., Wilson-Mendenhall, C. D., Duncan, E., & Barsalou, L. W. (2012). Mind wandering and attention during focused meditation: a fine-grained temporal analysis of fluctuating cognitive states. *Neuroimage*, *59*(1), 750-760.

Hawkins, G. E., Mittner, M., Boekel, W., Heathcote, A., & Forstmann, B. U. (2015). Toward a model-based cognitive neuroscience of mind wandering. *Neuroscience, 310*, 290-305.

Heathcote, A., Popiel, S. J., & Mewhort, D. J. (1991). Analysis of response time distributions: An example using the Stroop task. *Psychological Bulletin, 109*(2), 340.

Henríquez, R. A., Chica, A. B., Billeke, P., & Bartolomeo, P. (2016). Fluctuating minds: spontaneous psychophysical variability during mind-wandering. *PLoS one*, *11*(2)

Hohle, R. H. (1965). Inferred components of reaction times as functions of foreperiod duration. *Journal of Experimental Psychology, 69*(4), 382.

Joshi, S., Li, Y., Kalwani, R. M., & Gold, J. I. (2016). Relationships between pupil diameter and neuronal activity in the locus coeruleus, colliculi, and cingulate cortex. *Neuron*, *89*(1), 221-234.

Kahneman, D. (1973). *Attention and effort* (p. 246). Englewood Cliffs, NJ: Prentice-Hall.

Kane, M. J., Gross, G. M., Chun, C. A., Smeekens, B. A., Meier, M. E., Silvia, P. J., & Kwapil, T. R. (2017). For whom the mind wanders, and when, varies across laboratory and daily-life settings. *Psychological Science, 28*(9), 1271-1289.

Klinger, E. (1999). Thought flow: Properties and mechanisms underlying shifts in content. In J. A. Singer & P. Salovey (Eds.), At play in the fields of consciousness: Essays in honor of Jerome L. Singer (pp. 29–50). Mahwah, NJ: Erlbaum.

Klinger, E., & Cox, W. M. (1987). Dimensions of thought flow in everyday life. *Imagination, Cognition and Personality*, *7*(2), 105-128.

Klinger, E., Marchetti, I., & Koster, E. H. (2018). The Neuroscience of Spontaneous Thought: An Evolving, Interdisciplinary Field. *The Oxford Handbook of Spontaneous Thought,* Fox, K.C.R., & Christoff, K (editors). Oxford University Press, United States

Kucyi, A., Esterman, M., Riley, C. S., & Valera, E. M. (2016a). Spontaneous default network activity reflects behavioral variability independent of mind-wandering. *Proceedings of the National Academy of Sciences*, *113*(48), 13899-13904.

Kucyi, A., Hove, M. J., Esterman, M., Hutchison, R. M., & Valera, E. M. (2016b). Dynamic brain network correlates of spontaneous fluctuations in attention. *Cerebral cortex*, *27*(3), 1831-1840.

Lenartowicz, A., Simpson, G. V., & Cohen, M. S. (2013). Perspective: Causes and functional significance of temporal variations in attention control. *Frontiers in Human Neuroscience*, *7,* 381.

Levinson, D. B., Smallwood, J., & Davidson, R. J. (2012). The persistence of thought evidence for a role of working memory in the maintenance of task-unrelated thinking. *Psychological Science*, *23*(4), 375-380.

Mason, M. F., Norton, M. I., Van Horn, J. D., Wegner, D. M., Grafton, S. T., & Macrae, C. N. (2007). Wandering minds: the default network and stimulus-independent thought. *Science*, *315*(5810), 393-395.

Matzke, D., & Wagenmakers, E. J. (2009). Psychological interpretation of the ex-Gaussian and shifted Wald parameters: A diffusion model analysis. *Psychonomic Bulletin & Review, 16*(5), 798-817.

McVay, J. C., & Kane, M. J. (2009). Conducting the train of thought: working memory capacity, goal neglect, and mind wandering in an executive-control task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(1), 196-204.

McVay, J. C., & Kane, M. J. (2010). Does mind wandering reflect executive function or executive failure? Comment on Smallwood and Schooler (2006) and Watkins (2008). *Psychological Bulletin*, *136*(2), 188-197.

McVay, J. C., & Kane, M. J. (2012). Why does working memory capacity predict variation in reading comprehension? On the influence of mind wandering and executive attention. *Journal of Experimental Psychology: General*, *141*(2), 302.

Mills, C., Raffaelli, Q., Irving, Z. C., Stan, D., & Christoff, K. (2018). Is an off-task mind a freely-moving mind? Examining the relationship between different dimensions of thought. *Consciousness and Cognition, 58,* 20-33.

Mittner, M., Boekel, W., Tucker, A. M., Turner, B. M., Heathcote, A., & Forstmann, B. U. (2014). When the brain takes a break: a model-based analysis of mind wandering. *Journal of Neuroscience, 34*(49), 16286-16295.

Mittner, M., Hawkins, G. E., Boekel, W., & Forstmann, B. U. (2016). A neural model of mind wandering. *Trends in Cognitive Sciences, 20*(8), 570-578.

Mooneyham, B. W., & Schooler, J. W. (2013). The costs and benefits of mind-wandering: a review. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale, 67*(1), 11.

Mrazek, M. D., Phillips, D. T., Franklin, M. S., Broadway, J. M., & Schooler, J. W. (2013). Young and restless: validation of the Mind-Wandering Questionnaire (MWQ) reveals disruptive impact of mind-wandering for youth. *Frontiers in Psychology, 4*, 560.

Olbrich, S., Mulert, C., Karch, S., Trenner, M., Leicht, G., Pogarell, O., & Hegerl, U. (2009). EEG-vigilance and BOLD effect during simultaneous EEG/fMRI measurement. *Neuroimage, 45*(2), 319-332.

Poudel, G. R., Innes, C. R., Bones, P. J., Watts, R., & Jones, R. D. (2014). Losing the struggle to stay awake: divergent thalamic and cortical activity during microsleeps. *Human Brain Mapping*, *35*(1), 257-269.

Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., & Shulman, G. L. (2001). A default mode of brain function. *Proceedings of the National Academy of Sciences*, *98*(2), 676-682.

Raichle, M. E. (2015). The brain's default mode network. *Annual Review of Neuroscience*, *38*, 433-447.

Ralph, B. C., Onderwater, K., Thomson, D. R., & Smilek, D. (2017). Disrupting monotony while increasing demand: benefits of rest and intervening tasks on vigilance. *Psychological Research*, *81*(2), 432-444.

Rissman, J., Gazzaley, A., & D'Esposito, M. (2004). Measuring functional connectivity During distinct stages of a cognitive task. *Neuroimage, 23*(2), 752-763.

Schad, D. J., Nuthmann, A., & Engbert, R. (2012). Your mind wanders weakly, your mind wanders deeply: objective measures reveal mindless reading at different levels. *Cognition*, *125*(2), 179-194.

Schmiedek, F., Oberauer, K., Wilhelm, O., Süß, H. M., & Wittmann, W. W. (2007). Individual differences in components of reaction time distributions and their relations to working memory and intelligence. *Journal of Experimental Psychology: General, 136*(3), 414.

Schooler, J. W. (2011). Pupillometric evidence for the decoupling of attention from perceptual input during offline thought. *PloS One, 6*(3)

Seeley, W. W., Menon, V., Schatzberg, A. F., Keller, J., Glover, G. H., Kenna, H., ... & Greicius, M. D. (2007). Dissociable intrinsic connectivity networks for salience processing and executive control. *The Journal of neuroscience*, *27*(9), 2349-2356.

Seli, P., Cheyne, J. A., & Smilek, D. (2013). Wandering minds and wavering rhythms: Linking mind wandering and behavioral variability. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(1), 1-5.

Seli, P., Cheyne, J. A., Xu, M., Purdon, C., & Smilek, D. (2015). Motivation, intentionality, and mind wandering: Implications for assessments of task-unrelated thought. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41*(5), 1417.

Seli, P., Kane, M. J., Smallwood, J., Schacter, D. L., Maillet, D., Schooler, J. W., & Smilek, D. (2018a). Mind-wandering as a natural kind: A family-resemblances view. *Trends in cognitive sciences*, *22*(6), 479-490.

Seli, P., Konishi, M., Risko, E. F., & Smilek, D. (2018). The role of task difficulty in theoretical accounts of mind wandering. *Consciousness and Cognition, 65*, 255-262.

Seli, P., Risko, E. F., & Smilek, D. (2016). On the necessity of distinguishing between unintentional and intentional mind wandering. *Psychological Science*, *27*(5), 685-691.

Seli, P., Risko, E. F., Smilek, D., & Schacter, D. L. (2016b). Mind-wandering with and without intention. *Trends in Cognitive Sciences*, *20*(8), 605-617.

Serences, J. T., & Saproo, S. (2012). Computational advances towards linking BOLD and behavior. *Neuropsychologia, 50*(4), 435-446.

Singer, J. L., & McCraven, V. G. (1961). Some characteristics of adult daydreaming. *The Journal of Psychology*, *51*(1), 151-164.

Singer, J. L., & Schonbar, R. A. (1961). Correlates of daydreaming: a dimension of self-awareness. *Journal of Consulting Psychology*, *25*(1), 1.

Smallwood, J. (2013). Distinguishing how from why the mind wanders: a process–occurrence framework for self-generated mental activity. *Psychological Bulletin*, *139*(3), 519.

Smallwood, J., & Andrews-Hanna, J. (2013). Not all minds that wander are lost: the importance of a balanced perspective on the mind-wandering state. *Frontiers in psychology*, *4*, 441.

Smallwood, J., Brown, K. S., Baird, B., Mrazek, M. D., Franklin, M. S., & Schooler, J. W. (2012). Insulation for daydreams: a role for tonic norepinephrine in the facilitation of internally guided thought. *PloS one*, *7*(4)

Smallwood, J., Brown, K. S., Tipper, C., Giesbrecht, B., Franklin, M. S., Mrazek, M. D., ... & Schooler, J. W. (2011). Pupillometric evidence for the decoupling of attention from perceptual input during offline thought. *PloS One*, *6*(3), e18298.

Smallwood, J., Nind, L., & O'Connor, R. C. (2009). When is your head at? An exploration of the factors associated with the temporal focus of the wandering mind. *Consciousness and Cognition*, *18*(1), 118-125.

Smallwood, J., & Schooler, J. W. (2006). The restless mind. *Psychological Bulletin, 132*(6), 946.

Smallwood, J., & Schooler, J. W. (2015). The science of mind wandering: empirically navigating the stream of consciousness. Annual Review of Psychology, *66*, 487-518.

Spreng, R. N. (2012). The fallacy of a “task-negative” network. *Frontiers in Psychology, 3*, 145.

Spreng, R. N., Sepulcre, J., Turner, G. R., Stevens, W. D., & Schacter, D. L. (2013). Intrinsic architecture underlying the relations among the default, dorsal attention, and frontoparietal control networks of the human brain. *Journal of Cognitive Neuroscience*, *25*(1), 74-86.

Spreng, R. N., Stevens, W. D., Chamberlain, J. P., Gilmore, A. W., & Schacter, D. L. (2010). Default network activity, coupled with the frontoparietal control network, supports goal-directed cognition. *Neuroimage*, *53*(1), 303-317.

Stawarczyk, D., Majerus, S., Maj, M., Van der Linden, M., & D'Argembeau, A. (2011a). Mind-wandering: phenomenology and function as assessed with a novel experience sampling method. *Acta Psychologica*, *136*(3), 370-381.

Stawarczyk, D., Majerus, S., Maquet, P., & D'Argembeau, A. (2011b). Neural correlates of ongoing conscious experience: both task-unrelatedness and stimulus-independence are related to default network activity. *PloS One, 6*(2), e16997.

Teasdale, J. D., Proctor, L., Lloyd, C. A., & Baddeley, A. D. (1993). Working memory and stimulus-independent thought: Effects of memory load and presentation rate. *European Journal of Cognitive Psychology*, *5*(4), 417-433.

Unsworth, N., Redick, T. S., Lakey, C. E., & Young, D. L. (2010). Lapses in sustained attention and their relation to executive control and fluid abilities: An individual differences investigation. *Intelligence, 38*(1), 111-122.

Unsworth, N., & Robison, M. K. (2016). Pupillary correlates of lapses of sustained attention. *Cognitive, Affective, & Behavioral Neuroscience*, 1-15.

Unsworth, N., & Robison, M. K. (2018). Tracking arousal state and mind wandering with pupillometry. *Cognitive, Affective, & Behavioral Neuroscience, 18*(4), 638-664.

Vanhaudenhuyse, A., Demertzi, A., Schabus, M., Noirhomme, Q., Bredart, S., Boly, M., ... & Laureys, S. (2011). Two distinct neuronal networks mediate the awareness of environment and of self. *Journal of Cognitive Neuroscience*, *23*(3), 570-578.

Weissman, D. H., Roberts, K. C., Visscher, K. M., & Woldorff, M. G. (2006). The neural bases of momentary lapses in attention. *Nature Neuroscience, 9*(7), 971.

Yeo, B. T., Krienen, F. M., Sepulcre, J., Sabuncu, M. R., Lashkari, D., Hollinshead, M., ... & Fischl, B. (2011). The organization of the human cerebral cortex estimated by intrinsic functional connectivity. *Journal of Neurophysiology, 106*(3), 1125-1165.

Zabelina, D. L., & Andrews-Hanna, J. R. (2016). Dynamic network interactions supporting internally-oriented cognition. *Current Opinion in Neurobiology*, *40*, 86-93.